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WORKSHOP ON  
EARLY CRUSTAL GENESIS:  
THE WORLD'S OLDEST ROCKS



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WORKSHOP ON

EARLY CRUSTAL GENESIS:

THE WORLD'S OLDEST ROCKS

Edited by  
L. D. Ashwal

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ORIGINAL PAGE IS  
OF POOR QUALITY

Seated (left to right), Victor R. McGregor, John W. Valley, Kenneth D. Collerson, Fred Barker, William C. Phinney, Kevin Burke, Feiko Kalsbeek, John A. Percival, Lewis D. Ashwal. Standing (left to right), Alan M. Goodwin, John Gittins, Gene LaBerge, Karl R. Wirth, Allen Nutman, Clark R.L. Friend, Pamela A. Jones, A. Bruce Ryan, Carol D. Frost, James F. Hays, Donald R. Lowe, Zell E. Peterman, Gary P. Beakhouse, Robert Kay, Paul J. Sylvester, Cyrena A. Goodrich, M. Allen Kays, Kenneth D. Card, Scott Smithson, Gerard Gruau, Hans Sivertsen (boat captain), Lasse Schiotte, Stein B. Jacobsen. Photo taken at the Qôrqu Hotel, June 29, 1985.



# Introduction

The Earth is a dynamic planet, and much of the record of its early history has been destroyed. Although fragments of ancient crust remain, these constitute only a tiny fraction of the present continents. Therefore, areas of early Archean crust, with ages in excess of 3 billion years have been studied intensively in hopes of providing clues as to the nature of early Earth processes.

The Archean rocks of West Greenland, of interest for decades because of their antiquity, complexity, and magnificent exposure, were put into modern perspective by V.R. McGregor. He established the key geological relationships between major rock units; these were later confirmed by detailed geochronology, and led to the recognition of the oldest rocks on Earth. Through McGregor's mapping and interpretation, the Godthåbsfjord region has become a classic area to which all other Archean sequences are compared.

For those of us who had only read about this terrane, the possibility of examining first-hand these now-classic, yet remote exposures seemed exciting indeed. In early 1984, Pam Jones and Vic McGregor began looking into the seemingly impossible logistical arrangements for a field workshop to the area. Funding was requested and approved through the Lunar and Planetary Institute, the National Aeronautics and Space Administration, and the U.S. National Science Foundation, and the support and sponsorship of appropriate agencies in Copenhagen and Godthåb was obtained. On June 20, 1985, at 4:40 A.M., 27 of 32 participating scientists from 6 countries boarded a C-141 military transport jet at McGuire Air Force Base in New Jersey, bound for West Greenland. For 5 days we sailed through the fjords of West Greenland and were transported by small dinghys to the outcrops, where Vic McGregor and his colleagues Clark Friend and Alan Nutman showed us the wonders of Greenland's Archean geology. Uncooperative weather, a threat which loomed in our minds to subvert the field trips, turned out not to be a problem. Surprisingly, no one fell into the water, and the seasickness was taken care of by scopolamine. Perhaps most spectacular were the helicopter excursions to see the world's oldest supracrustal rocks at Isua. There were also two full days of technical sessions which included oral and poster presentations and lively discussions about some of the controversial aspects of the geology.

This volume contains extended abstracts of the talks at the technical sessions, summaries of attendant discussions, up-to-date accounts of the geology of the Godthåbsfjord and Isukasia areas, and detailed field trip guides for both regions. This report should, therefore, serve as a comprehensive source book for those interested in learning about the geology of the world's oldest rocks, or visiting the outcrops themselves.

L.D. Ashwal  
Houston  
November, 1985

# Program

## Session One: General Reviews of Precambrian Crustal Evolution

**K. Burke, Chairman**  
**L. D. Ashwal, Summarizer**

Cyclic Growth in Atlantic Region Continental Crust

*A. M. Goodwin*

Petrogenesis of Calcic Plagioclase Megacrysts in Archean Rocks

*W. C. Phinney, D. A. Morrison, and D. E. Maczuga*

Some Examples of Deep Structure of the Archean From Geophysics

*S. B. Smithson, R. A. Johnson, and W. R. Pierson*

Varying Rock Responses as an Indicator of Changes in CO<sub>2</sub>-H<sub>2</sub>O Fluid Composition

*C. R. L. Friend*

A Model for the Biological Precipitation of Precambrian Iron-Formation

*Gene L. LaBerge*

Archean Sedimentary Styles and Early Crustal Evolution

*Donald R. Lowe*

## Session Two: Geology and Geochemistry of the Archean Craton in Greenland and Labrador

**R. Kay, Chairman**  
**Z. E. Peterman, Summarizer**

Pb Isotopic Evidence for Early Archaeæan Crust in South Greenland

*Paul N. Taylor and Feiko Kalsbeek*

Age and Origin of Gneisses South of Ameralik, Between Kangimut-Sangmissoq and Qasigianguit

*N. W. Jones, S. Moorbath, and P. N. Taylor*

Regional Variation in the Amitsoq Gneisses Related to Crustal Levels During Late Archean Granulite Facies Metamorphism, Southern West Greenland

*A. P. Nutman, D. Bridgwater, and V. R. McGregor*

Strontium and Neodymium Isotopic Variations in Early Archean Gneisses Affected by Middle to Late Archean High-Grade Metamorphic Processes: West Greenland and Labrador

*K. D. Collerson, M. T. McCulloch, D. Bridgwater, V. R. McGregor, and A. P. Nutman*

Intrusions of Mixed Origin Migmatizing Early Archaeæan Crust in Northern Labrador, Canada

*L. Schiøtte and D. Bridgwater*

Significance of the Sm-Nd Isotopic Systematics of the Akilia Association

*G. Gruau, A. Nutman, and B. M. Jahn*

Archean Metamorphic Sequence and Surfaces, Kangerdlugssuaq Fjord, East Greenland

*M. A. Kays*

Metamorphosed Ultramafic Rocks in East Greenland

*M. A. Kays and M. J. Dorais*

### **Session Three: Precambrian Crustal Evolution in North and South America**

**F. Kalsbeek, Chairman**

**F. Barker, Summarizer**

**Geology and Tectonics of the Archean Superior Province, Canadian Shield**

*K. D. Card*

**Metamorphism and Plutonism in the Quetico Belt, Superior Province, N. W. Ontario**

*J. A. Percival*

**Speculations on Nature and Extent of Archean Basement in Labrador as Indicated by Sr, Nd, and Pb Isotopic Systematics of Proterozoic Intrusives**

*L. D. Ashwal, J. L. Wooden, and R. F. Emslie*

**Geochemistry of Granitoid Rocks from the Western Superior Province—Evidence for 2- and 3-stage Crustal Evolution Models**

*G. P. Beakhouse and R. H. McNutt*

**Low CO<sub>2</sub>, Fluid-absent Metamorphism in the Adirondacks**

*John W. Valley*

**Early Archean Tonalite Gneiss in the Upper Peninsula of Michigan**

*Z. E. Peterman, R. E. Zartman, and P. K. Sims*

**Development of Archean Crust in the Wind River Mountains, Wyoming**

*C. D. Frost, B. R. Frost, M. E. Koesterer, T. P. Hulsebosch, and D. Bridgwater*

**Origin and Evolution of the Amazonian Craton**

*A. K. Gibbs and K. R. Wirth*

#### **Poster**

**Partial Melting of Amphibolite to Trondhjemite near Yakutat, Alaska**

*F. Barker*



# Summaries

## Session One: General Reviews of Precambrian Crustal Evolution

Summarized by Lewis D. Ashwal

This session opened with a talk by A.M. Goodwin on the cyclicity of continental growth in the "Atlantic" region, including North and South America, Europe, Africa, Arabia, and Madagascar. Goodwin estimated the areal proportions of combined (exposed + buried) crust of Precambrian age as: 46% late Proterozoic (0.6–1.0 Ga), 18% mid-Proterozoic (1.0–1.8 Ga), 22% early Proterozoic (1.8–2.6), and 14% Archean (pre 2.6 Ga). As pointed out in the discussion, however, these averages cannot be used to make inferences about secular continental growth because the classification is based on radiometric ages, uncorrected for reworking and reactivation by later orogenic events. Goodwin endorsed Gastil's (1960) suggestion of a roughly 400 Ma periodicity in global orogeny and accelerated crustal growth. One explanation for this, following the model of LePichon and Huchon (1984) involves periodic break-up and re-assembly of a supercontinent, with dispersal caused by excessive heating of the upper mantle due to the insulating continental cap. In discussion, K. Burke suggested that the cyclicity in the Precambrian rock record might be merely an apparent artifact of what has been preserved, and along the same lines, Z.E. Peterman pointed out that there are many events which do not fit the 400 Ma periodicity.

W.C. Phinney discussed the petrogenesis of equidimensional, calcic ( $An_{80-90}$ ) plagioclase megacrysts which characterize Archean anorthosite complexes, and which also occur in mafic sills, dikes, and flows throughout most Archean cratons. Attempts to use REE partition coefficients to determine the melt compositions from which the megacrysts precipitated are hampered by the effects of alteration, contamination, and recrystallization, and also by uncertainties in selecting an appropriate set of partition coefficients. Analyses of fresh plagioclases, free of alteration, from the Bad Vermilion Lake anorthosite complex, Ontario indicate reasonable melt compositions (LREE depleted patterns, 20–30X chondrites, similar to primitive Archean tholeiites) if the newly-determined plagioclase partition coefficients of G.A. McKay are used. This approach, if applied, for example, to megacrysts in mafic dikes, could be used to assess whether the plagioclases are in equilibrium with their mafic matrices, and may provide clues as to the extent of contamination of these mafic melts as they ascended

through the crust. Phinney also discussed his model for megacryst origin, involving ponding of mantle-derived mafic melts near the Moho, crystallization and separation (perhaps by flotation) of large, equidimensional plagioclases, and transport of crystal-laden melts and mushes to the surface or emplacement at shallow depths. In discussion, R. Kay questioned whether there was any independent evidence for the depth of crystallization of the megacrysts—evidently not. K. Burke wondered if these occurrences are truly restricted to the Archean, and we learned from Phinney that there are megacrysts of calcic plagioclase ( $An_{85}$ ) up to 8 cm across in recent basalts from the Galapagos!

S.B. Smithson (and coauthors R.A. Johnson and W.R. Pierson) discussed geophysical constraints on the structure of the deep crust, and implications for Archean crustal development. COCORP reflection seismic data indicate that the boundary between the early Archean (3.6–3.8 Ga) gneiss terrane of Minnesota and the later Archean granite-greenstone terrane dips gently to the north rather than steeply or vertically, as previously assumed. A similar result is obtained from magnetic modelling, and the boundary is interpreted as an Archean suture formed during accretion of the greenstone belts to the older gneiss terrane. Seismic data for the gneiss terrane indicates the presence of foliated and/or layered rocks to depths of at least 30 km; this represents either a supracrustal sequence or a large-scale migmatite terrane. COCORP data also nicely reveal the Cretaceous thrust which exposed the Archean Wind River Range in the Wyoming Province, but more importantly, the presence of complex arcuate reflectors to depths of 20–30 km can be interpreted as large-scale recumbently folded gneisses similar to those exposed in the core of the range. The boundary between the Archean Wyoming Province and the early Proterozoic terrane in southeastern Wyoming does not show up clearly on seismic profiles, perhaps because it dips steeply. Gravity data indicates an abrupt change in crustal structure across this boundary; Proterozoic crust is either thicker or less dense than adjacent Archean crust, and this difference has apparently persisted since the mid-Proterozoic. A general question raised in discussion related to the degree of confidence with which features in reflection profiles can be correlated to specific geologic structures. Arcuate reflection patterns, for example, can be interpreted in many ways, including a variety of fold patterns, domal structures, or intrusive features.

C.R.L. Friend discussed the role of fluids in the formation of charnockites in south India. In Kabbaldurga quarry, at the transition zone between granulite and amphibolite facies, charnockitization took place along

shear zones and via a rectilinear network of veins oblique to the preexisting fabric of the rocks. Friend suggested that these represent pathways along which carbonic fluids were introduced, and charnockites formed by dehydration during prograde metamorphism. Friend's model involves influx of CO<sub>2</sub> from greater depths, and flushing out and accumulation of H<sub>2</sub>O ahead of the CO<sub>2</sub> "front." Accumulation of aqueous fluids in amphibolite facies rocks caused local partial melting, which accounts for the intimate association of charnockite veins and anatectic granites. Although channelization of carbonic fluids appears able to account for the charnockites at Kabbaldurga, the regime of fluid flow responsible for the formation of large areas of massive charnockite to the south remains uncertain. In some areas, networks of charnockite veins are gradational into solid, massive charnockites, suggesting the possibility that channelized fluids were responsible for producing both textural types. In the discussion of this paper, both J.W. Valley and R. Kay pointed out that CO<sub>2</sub> and H<sub>2</sub>O should be miscible at the conditions of charnockitization (750°C, 7.5 kbar), and questioned the likelihood of a discrete "front" of CO<sub>2</sub> in contact with dominantly aqueous fluid. In response, Friend commented that the miscibility of CO<sub>2</sub> and saline aqueous fluid at high pressure is not known. K.D. Collerson raised the question of the source of the CO<sub>2</sub>; Friend favors a mantle source over one involving decarbonation of supracrustal rocks.

G.L. LaBerge presented his biological model for the precipitation of Precambrian iron formations. Assuming an oxygen-deficient atmosphere and water column to allow sufficient Fe solubility, LaBerge proposed that local oxidizing environments, produced biologically, led to precipitation of iron formations. He further suggested that spheroidal structures about 30 µm in diameter, which are widespread in low-grade cherty iron formations, are relict forms of the organic-walled microfossil *Eosphaera tylerii*. The presence of these structures suggests that the organism may have had a siliceous test, which allowed sufficient rigidity for accumulation and preservation. LaBerge's model involves precipitation of ferric hydrates by oxidation of iron in the photic zone by a variety of photosynthetic organisms. Silica may have formed in the frustules of silica-secreting organisms, including *Eosphaera tylerii*. Iron formations formed, therefore, by a sediment rain of biologically produced ferric hydrates and silica and other organic material. Siderite and hematite formed diagenetically on basin floors, and subsequent metamorphism produced magnetite and iron silicates. A.P. Nutman inquired about the fate of these spheroidal structures during metamorphism, to which LaBerge responded that he has not recognized fossil-like features

in ironstones at grades higher than lower greenschist. K. Burke questioned the assumption of an oxygen-deficient Precambrian atmosphere, pointing out that there is some evidence to the contrary.

The session ended with a talk by D.R. Lowe on the distinctions between and implications of early and late Archean sedimentary styles. Early Archean (pre 3.0 Ga) greenstone belts, such as the Barberton of South Africa and those in the eastern Pilbara Block of Australia are characterized by fresh or slightly reworked pyroclastic debris, orthochemical sediments such as carbonates, evaporites, and silica, and biogenic deposits including cherts and stromatolitic units. Terrigenous deposits are rare, and Lowe suggests that early Archean sediments were deposited on shallow simatic platforms, with little or no components derived from sialic sources. In contrast, late Archean greenstone belts in the Canadian Shield and in the Yilgarn Block of Australia contain coarse terrigenous clastic rocks including conglomerate, sandstone, and shale derived largely from older greenstone belts, but these rocks also contain detritus from sialic basement. Deposition appears to have taken place in deep-water, tectonically unstable environments. Lowe interprets these observations to indicate that the early Archean greenstone belts formed as anorogenic, shallow-water, simatic platforms, with little or no underlying or adjacent continental crust, an environment similar to modern oceanic islands formed over hot spots. These units underwent cratonization, and late Archean greenstone belts formed in deeper-water, tectonically active depositional sites. In the discussion, F. Barker pointed out that 3.5 Ga conglomerates from the Moodies Group in the Barberton greenstone belt contain abundant granitic clasts, presumably derived from the adjacent 3.55 Ga ancient gneiss complex. Lowe indicated that ages of events in the Barberton belt are not known with certainty, and that there was a major hiatus in the sedimentary record before deposition of the Moodies Group. C.R.L. Friend commented that Lowe's picture of a relatively quiescent early Archean Earth is different than the views of most other geologists, who favor more violent and tectonically active conditions during that period. Lowe responded with a suggestion that early Archean greenstone belts may have formed quite rapidly.

## Session Two: Geology and Geochemistry of the Archean Craton in Greenland and Labrador

Summarized by Zell E. Peterman

Whether or not Rb-Sr, Sm-Nd, and Pb-Pb isotopic systems at the whole-rock scale can be completely reset

in polymetamorphic terranes that have been retrograded from granulite to lower grades, with all vestiges of earlier history being obliterated, was a central issue in the session on "Geology and Geochemistry of the Archean Craton in Greenland and Labrador". Emphasis focussed on an area along the south side of the Ameralik fjord called Kangimut sangmissoq which Vic McGregor referred to as "...the most controversial, but perhaps the most important locality to be visited during the workshop."

Alan Nutman in his presentation on "Regional Variation in the Amîtsoq Gneisses Related to Crustal Levels During Late Archean Granulite Facies Metamorphism, southern west Greenland" (with Bridgwater and McGregor), described the dominant lithology at Kangimut sangmissoq as nebulitic tonalitic gneiss containing highly distended plagioclase phyrlic amphibolites. The gneiss-amphibolite complex was intruded by Nûk gneiss between 3.05 and 2.90 Ga and later (2.6-2.7 Ga) by post-granulite facies granitoid sheets. The amphibolites are thought to be Ameralik dikes and the older gray gneisses are then Amîtsoq by definition. The problem arises when the isotopic data are considered, none of which indicate rocks older than about 3.0 Ga.

Paul Taylor ("Age and Origin of Gneisses South of Ameralik, between Kangimut sangmissoq and Qasigiánguit," by N. W. Jones, S. Moorbath, and Taylor) presented the isotopic age data for the so-called Amîtsoq gneisses (referred to as K-s-Q gneisses) that contradicted the age assignment based on field relations. Taylor summarized the Oxford position by stating that the isotopic data preclude either direct correlation of K-s-Q and Amîtsoq gneisses, or derivation of the K-s-Q gneisses, from Amîtsoq gneisses by magmatic or metamorphic reworking. To support this contention Taylor presented data for six samples of the gray gneiss that yielded a Sm-Nd isochron of  $2825 \pm 125$  Ma with an initial  $\epsilon_{Nd}$  of +2.2. This contrasts with an isochron of  $3627 \pm 48$  Ma (initial  $\epsilon_{Nd} = +1.7$ ) for eleven samples of Amîtsoq gneisses collected from less controversial areas. He emphasized the implications of the positive initial for the K-s-Q gneisses in terms of precluding any significant component of substantially older crustal material. The K-s-Q gneisses are dramatically depleted in Rb, but six samples selected on the basis of higher Rb contents define a Rb-Sr isochron of  $2770 \pm 185$  Ma (MSWD = 4.1) with an initial of  $0.70195 \pm 54$ . Taylor compared these data with Amîtsoq gneiss data to show that the average Amîtsoq would have had significantly greater  $^{87}\text{Sr}/^{86}\text{Sr}$  at 2.8 Ga than the initial  $^{87}\text{Sr}/^{86}\text{Sr}$  value of 0.70195 shown by the K-s-Q gneisses.

Taylor concluded his isotopic arguments with a set of whole-rock Pb-isotope analyses for 18 samples of

K-s-Q gneisses. He interpreted the data in the context of a crustal contamination model for the Nûk gneisses that he and coworkers published in 1980. Pb-isotope data for the K-s-Q gneisses plot on or below an 2.9-Ga isochron for uncontaminated Nûk gneisses, indicating some interaction with Amîtsoq Pb but generally less than that shown by most Nûk gneisses. He interpreted the data set to indicate a large proportion of the Pb having been derived from a juvenile source during the Late Archean.

Ken Collerson ("Strontium and Neodymium Isotopic Variations in Early Archean Gneisses Affected by Middle and Late Archean High-grade Metamorphic Processes: West Greenland and Labrador", by Collerson, M. T. McCulloch, D. Bridgwater, V. R. McGregor, and A. P. Nutman) presented a somewhat contradictory interpretation based on isotopic data for K-s-Q gneisses. Whole-rock Rb-Sr data for a large set of K-s-Q samples were in agreement with the Oxford data giving an isochron of  $2768 \pm 264$  Ma (IR of  $0.7017 \pm 5$ ) but with substantially more scatter (MSWD = 79). Sm-Nd data on two samples of K-s-Q gneisses yielded CHUR model ages of 2625 and 2508 Ma.

Collerson presented similar data for Amîtsoq gneiss from Nordafar about 55 km southwest of Kangimut sangmissoq. Here a strongly deformed assemblage of units includes Amîtsoq gneiss and Ameralik dikes interleaved with Malene supracrustals, Nûk gneiss, and metagabbro associated with a nearby anorthosite complex. Eight samples of Amîtsoq gneiss from Nordafar yielded a badly scattered Rb-Sr whole-rock isochron of  $3001^{+193}_{-153}$  Ma and an  $I_{Sr}$  of  $0.7021^{+20}_{-17}$ . Two samples yielded Sm-Nd model ages of 3.4 and 3.2 Ga.

Collerson interpreted the Kangimut sangmissoq and Nordafar data, with supporting evidence from Uivak and Kiyuktok gneisses in Labrador, as reflecting a Late Archean event that resulted in mixing of Early Archean gneiss (Amîtsoq and equivalents) with a juvenile-like component injected at about 2.9 Ga. The resulting isotopic systematics, further clouded by hydrous retrogression of the granulite-facies mineralogy, emphasize the younger event.

Discussions that followed these presentations probed at uncovering any additional points that might shed light on the seemingly contradictory field and isotopic evidence for Kangimut sangmissoq. Alan Nutman emphasized the difficulty of distinguishing between the Nûk and Amîtsoq solely on the basis of lithology (without the benefit of Ameralik dikes), and Clark Friend suggested the Amîtsoq at Kangimut sangmissoq may have been extensively permeated by Nûk gneiss with the amphibolite dikes surviving as discrete but highly deformed bodies. In this

scenario, the problem becomes one of proportions of Nûk and Amîtsoq rather than an either/or choice between the two.

Subsequent examination of outcrops at Kangimut sangmissoq did not lead to a unanimity of opinion regarding the dichotomy between field relations and isotopic ages (see summary by Frost and Goodwin, this report). Those with a field bent tended to accept the evidence for the gray gneisses being Amîtsoq, whereas those with isotopic connections retained some skepticism regarding the contention that the isotopic systems had been totally reset.

A major gap in the isotopic data base for this critical region is the lack of a systematic U-Pb zircon study. One analysis attributed to H. Baadsgaard is ambiguous as it plots on the intersection of chords for the Akilia association (3.8 Ga) and the Nûk gneisses (3.0 Ga). Further isotopic elucidation will require a detailed zircon study with careful attention to sampling and avoidance of ductile shear zones that are common in the outcrops. Additional Rb-Sr, Sm-Nd, and Pb-Pb studies that could lead to the identification and assessment of the proportions of various age components present should also be done in the context of a carefully designed sampling protocol. Further discussion of the current isotopic and field data is moot until such new studies are completed.

In a relevant study in northern Labrador, L. Schiøtte described migmatization of Early Archean Uivak gneisses by Late Archean granitic and trondhjemitic injections ("Intrusion of Mixed Origin Migmatizing Early Archean Crust in northern Labrador, Canada," with D. Bridgwater). The REE, major element, and isotopic geochemistry of the felsic sheets is interpreted to indicate both mantle and crustal components, and the sheets with associated fluids were the vehicle for element transport in the crustal column with attendant isotopic modification of the older gneisses.

Isotopic ambiguities were not restricted to retrograded Amîtsoq (or Nûk) at Kangimut sangmissoq. G. Gruau from Rennes reported a Sm-Nd study of metavolcanic rocks from the pre-Amîtsoq Akilia association ("Significance of the Sm-Nd Isotopic Systematics of the Akilia Association," with A. Nutman and B. M. Jahn). Fourteen samples of mafic and ultramafic rocks plotted in a band bounded by 3.6 Ga isochrons. Gruau offered two interpretations of this data set. In the context of a 3.6-Ga granulite facies metamorphism and a 2.6-Ga retrograde event, Gruau speculated that the scatter could reflect post-crystallization open-system behavior. His

second interpretation involved numerical separation of the data into two discrete sets with no independent evidence for doing so. These two sets define tight Sm-Nd isochrons at  $3,887 \pm 65$  Ma (MSWD = 0.7) and  $3,112 \pm 154$  Ma (MSWD = 4.3) with initial  $\epsilon_{Nd}$  values of +4.2 and +1.0, respectively. With reference to the second interpretation, Gruau speculated that the sampling may have inadvertently included the younger Malene supracrustals along with the Akilia association noting that the units have very similar lithologic components.

On a more regional scale, Paul Taylor presented the results of an isotopic remote sensing study focussed on delineating the extent of Early Archean crust north and south of the Nuuk area and in south Greenland ("Pb Isotope Evidence for Early Archean Crust in South Greenland", with Feiko Kalsbeek). Contamination of the Late Archean Nûk gneisses and equivalents by unradiogenic Pb uniquely characteristic of Amîtsoq gneiss was detected as far south as Sermilik about 70 km south of Nuuk and only as far north as the mouth of Godthåbsfjord. This study was extended to the southern part of the Archean craton and the adjoining Early Proterozoic Ketilidian orogenic belt where the Pb isotopes suggest several episodes of reworking of older uranium-depleted continental crust. The technique of using the Pb isotopic character of younger felsic rocks, in this case Late Archean and Early Proterozoic gneisses and granites, to sense the age and isotopic character of older components is a particularly powerful tool for reconstructing the evolutionary growth and development of continental crust.

In two papers, M. Kays described Archean sequences in east Greenland ("Archean Metamorphic Sequence and Surfaces, Kangerdlugssuaq Fjord, East Greenland" and "Metamorphosed Ultramafic Rocks in East Greenland", with M. J. Dorais). Isotopic dating control is sparse here, but Kay and coworkers have erected a detailed relative chronology involving seven major events based on detailed mapping of metamorphic surfaces, structures and fabrics. A supracrustal sequence including pelites, quartzites, and iron-formation and an associated gneiss complex were intruded by 3.0-Ga gneisses. Pod-like ultramafic bodies occur in the supracrustal sequence as remnants of dikes and sills. Kay noted that such ultramafic bodies are common in pre-2.9-Ga supracrustals in Labrador, southwest Greenland, southeast Greenland and in the Lewisian of northwest Scotland. He speculated that these may mark a single major event in the evolution of the Middle Archean of North Atlantic craton.

### Session Three: Precambrian Crustal Evolution in North and South America

Summarized by Fred Barker

Session Three, on North and South America, consisted of eight talks and a poster session.

K.D. Card presented a summary of the Archean Superior Province. Forming the bulk of the Canadian Shield and being Earth's largest single exposure of Archean rocks at 2,200 km in strike length of individual subprovinces and 1,200 km in across-strike width, Superior Province shows systematic patterns of several types of subprovince or lithotectonic terranes. The province is bounded on the north (Pikwitonei and Minto subprovinces) and south (Minnesota River Valley and Upper Peninsula-Michigan subprovince) by high-grade gray gneiss complexes. These are older than the intervening bulk of the province: Minnesota-Michigan rocks in part are older than 3.5 Ga, whereas the Pikwitonei-Minto subprovinces are not yet well dated; most of Superior Province is 3.0-2.65 Ga old.

Most of Superior Province consists of alternating belts of largely volcanic rocks and of largely sedimentary rocks, each belt 30 to several hundred km in breadth. Both types are metamorphosed, tectonized and intruded by abundant plutonic rocks. The metavolcanic or "greenstone" belts show initial komatiitic-tholeiitic volcanism (komatiite-tholeiite and basalt-andesite-dacite piles), then calc-alkaline type (basalt-andesite-dacite-rhyolite sequences) and ending with alkaline rocks. The alkaline volcanism tends to be associated with strike-slip faults. Volcanic sequences or cycles ca. 10 km thick and 100 km maximum horizontal dimension form the bulk of the metavolcanic belts. Volcanogenic sediments, chert and ironstone were deposited between and around the volcanic sequences. The metasedimentary belts are largely graywacke and pelite deposited as turbidites. Metamorphism of volcanic belts ranges from lower greenschist to upper amphibolite and locally to granulite facies, whereas that of sedimentary belts ranges from low greenschist to granulite facies. Deformation of metavolcanic belts typically into sinuous isoclinal folds is simpler than that of metasedimentary belts, where early recumbent folds and dome-basin structures were strongly deformed to give subhorizontal isoclinal folds and gentle lineations. Plutonic sequences in metavolcanic belts typically consist of early, synvolcanic tonalite; trondhjemite and granodiorite, granodiorite of intermediate age; and late granite and syenite-diorite-gabbro suites. Some tonalite gneisses occur as pre-volcanic basement. Peraluminous, high-SiO<sub>2</sub> granites are the predominant type in metasedimentary belts.

Superior Province also contains belts, such as Behrens River and Bienville, that consist largely of orthogneiss and intermediate to felsic plutonic rocks: these are termed "plutonic" belts.

Major volcanism and plutonism occurred first in the northern part of Superior Province at 3.0-2.8 and 2.75-2.7 Ga, and then in the southern part at ca. 2.79-2.75 Ga. Deformation and metamorphism happened at 2.73-2.70 Ga in the north and 2.70-2.68 Ga in the south.

In consideration of the chemical similarity of volcanic rocks of the metavolcanic belts to those of Tertiary to modern island arcs, of the alternation of volcanic and sedimentary belts, of the north-to-south sequential age relations and of the deformation, Card suggested a plate-tectonic origin for Superior Province. The metavolcanic belts formed as intraoceanic island arcs; the metasedimentary belts as marginal basins; both arc and basin suites were successively accreted so that the southern margin of the Province moved southward; and the early plutonic rocks formed in the arcs, whereas the younger ones resulted from crustal melting in response to crustal thickening and high heat flow from the mantle.

J.A. Percival next considered metamorphism and plutonism in the Quetico Belt, Superior Province, which he has studied in Ontario for 350 km of its total 1,200-km length. The Quetico Belt lies between the metavolcanic Wawa-Shebandowan (to the south) and Wabigoon (to the north) Belts. It consists of marginal metasedimentary rocks and central pelitic, gneissic and plutonic rocks. Metamorphism is Barrovian, at depths less than 10 km, and grade increases from margins to core of the belt: the outermost pelites are at chlorite-muscovite grade; inward a garnet-andalusite zone formed throughout the inner margin; and the central zone ranges from garnet-andalusite in the west and garnet-sillimanite-muscovite (at Lac La Croix) to garnet-sillimanite-cordierite and rare kyanite 6-150 km to the east. This increase is correlated with granitic intrusives. Migmatites in the core have intrusive leucosomes in the west and locally derived ones in the east. Isograd surfaces are steep where the belt is narrow and dip gently where it is wide.

The Quetico Park (Ontario) intrusive complex of the central region of the Quetico Belt shows a zonation across its 20-50 km width from (1) older, marginal, medium-grained biotite  $\pm$  magnetite leucogranites of minimum-melt composition and associated tonalite and quartz diorite; to (2) younger, central, coarse to pegmatitic, strongly peraluminous granites (Sturgeon Lake batholith) variously containing garnet, muscovite, sillimanite, cordierite, biotite, apatite, tourmaline and fluorite. Xenoliths of the biotite leucogranites are igneous or

metagneous, those of the peraluminous granites are metasedimentary. The outer, or marginal, biotite leucogranites were derived from graywacke and/or igneous protoliths, whereas the central peraluminous granites came from pelitic protolith.

Sediment of the Quetico basin had its source in the bordering metavolcanic belts and was deposited ca. 2.75–2.70 Ga ago. Boundaries of the belt dip inward, so it essentially is a graben of inter-arc or back-arc type. Generation of the central region of the Quetico Belt of high metamorphic rank and abundant plutonic rocks probably was due to emplacement of mafic, mantle-derived magma in the uppermost mantle or lower crust. Percival also suggested that the southern Superior Province shows a tectonic style transitional from that of the Archean to that of the Proterozoic (ca. like that of modern plate tectonics).

L.D. Ashwal, J.L. Wooden and R.F. Emslie presented Sr, Nd and Pb isotopic results on Proterozoic intrusives in Labrador and used them to infer both the nature and extent of Archean basement along the boundary between the Nain and Grenville Provinces. They studied the Harp Lake and Mealy Mountains anorthosite complexes and crosscutting mafic dikes—the latter showing similar mineralogy, strike, and major-minor-elemental abundances in both areas—to give the following:

	Harp Lake Complex	Mealy Mountains Complex
Country	Nain Province, 3.6 Ga to ca. 2.7 Ga	Grenville Province, Proterozoic
Rocks:	reworked at 1.7–1.8 Ga.	
Intrusive Age	1.6–1.65 Ga	1.6–1.65 Ga
( $^{87}\text{Sr}/^{86}\text{Sr}$ ) <sub>o</sub>	0.7039–0.7066	0.7026–0.7032
$\epsilon_{\text{Nd}}$	–2.4 to –6.0	+1.2 to +3.0
Pb isotopes	Wide scatter, mixing between depleted Prot. mantle and older unradiogenic component	Linear array from model mantle to aver. crust

	Harp dikes	Mealy dikes
Age	1380 ± 54 Ma	ca. 1.4 Ga
( $^{87}\text{Sr}/^{86}\text{Sr}$ ) <sub>o</sub>	0.7032–0.7033	0.7025–0.7028
$\epsilon_{\text{Nd}}$	–0.3 to –2.3 (plot on ca. 3.3 Ga line)	+3.8 to +5.6
Pb isotopes	Low $^{207}\text{Pb}/^{204}\text{Pb}$	Like those of Mealy Mountains anorthosite complex

These authors pointed out that the Mealy Mountains anorthosite complex and its dikes, emplaced in rocks of the Grenville Province, are not contaminated by older crustal rocks, whereas the Harp Lake complex and dikes show contamination by high  $^{87}\text{Sr}/^{86}\text{Sr}$ , low  $\epsilon_{\text{Nd}}$  and U-depleted material—yet the Harp Lake rocks show little enrichment in  $\text{SiO}_2$ ,  $\text{K}_2\text{O}$  or  $\text{Na}_2\text{O}$ . Among possible contaminants of 3.6 Ga (Uivak Gneisses) to 1.7–1.8 Ga (Churchill gneisses of reworked late Archean rocks), Ashwal and coworkers favor less than 10% of low-Rb Uivak gneisses to produce the isotopic values of the Harp dikes. Thus Sr-Nd-Pb isotopes in Proterozoic mantle-derived intrusives may be used to show that in Labrador the Grenville Province is free of Archean crustal rocks and that the 3.6 Ga-age gneisses exposed at the Atlantic coast may extend inland as far west as the Labrador Trough.

G.P. Beakhouse and R.H. McNutt contrasted plutonism in two adjacent subprovinces of the western Superior Province—the Winnipeg River batholithic terrane and the Wabigoon greenstone-tonalite terrane. The Winnipeg River terrane consists of complex gneisses as old as 3.17 Ga, tonalite-trondhjemite plutons of both pre-tectonic (2.83 Ga or older) and syntectonic types, and potassic plutons of syn- to post-tectonic types (2.7–2.66 Ga). Volcanic supracrustal rocks are widespread but form less than 10% of the subprovince. Metamorphic grade is upper amphibolite to granulite facies, and the gneiss complexes and supracrustal rocks show *in situ* partial melting. The authors conclude that the tonalitic intrusives formed by partial melting of basaltic protolith, and that tonalitic rocks, in turn, were partially melted out of lower crust ca. 20 km thick to give the potassic plutons.



Beakhouse and McNutt's studies of the Alneau batholith of the Wabigoon terrane—a representative batholith—indicate that it is tonalitic to granodioritic, ranging from early, relatively darker migmatite to later, massive, light-colored variants. They suggested a plate-tectonic origin in which a Wabigoon island arc was accreted to pre-existing "Superioria" (as coined by the summarizer), here the Winnipeg batholith terrane. As "Wabigoonia" docked its volcanism ceased and at 2,710–2,705 m.y. domes (probably related to magmatism) and nappes developed.

In a paper pertinent to studies of granulite metamorphism in the Archean, J.W. Valley presented his results on late Proterozoic metamorphism of this grade in the Adirondacks. There more than 20,000 km<sup>2</sup> of rock are at granulite facies. Low H<sub>2</sub>O fugacities (ca. 0.1) are implied by orthopyroxene-bearing assemblages and by stability (relative to liquid) of k'spar-plag-quartz assemblages. After mentioning the popular concept of infiltration of CO<sub>2</sub> into Precambrian rocks and attendant generation of granulite facies assemblages, Valley summarized several features of Adirondack rocks pertinent to CO<sub>2</sub> and H<sub>2</sub>O during their metamorphism: wollastonite occurs in the northeast, whereas marble occurs in the western lowlands; contact metamorphism by anorthosite preceeding granulite metamorphism is indicated by oxygen isotopes.  $f_{O_2}$  lies below that of the QFM buffer; total  $P_{H_2O} + P_{CO_2}$  determined from monticellite-bearing assemblages are much less than  $P_{total}$  (7 to 7.6 kb). These and other features indicate close spatial association of high- and low- $P_{CO_2}$  assemblages and that a vapor phase was not present during metamorphism. Thus Adirondack rocks were not infiltrated by CO<sub>2</sub> vapor. Their metamorphism, at 625–775°C, occurred either when the protoliths were relatively dry or after dessication occurred by removal of a partial-melt phase.

Z.E. Peterman, R.E. Zartman and P.K. Sims presented their geochronological results on tonalite gneiss of northern Michigan that is 3.56 Ga or slightly older. Tonalitic augen gneiss and structurally overlying biotite gneiss and schist are exposed in a dome near Watersmeet. They are part of an extensive gneiss terrane of southern Minnesota, Wisconsin and Michigan that includes rocks of early to late Archean ages and lies south of the Wawa volcanic subprovince. Two samples of the augen gneiss and one of the biotite gneiss show zircon grains of similar shape, zoning, color and development of crystal faces. These zircons give Pb/U isotopic ratios that plot on a chord of  $3,560 \pm 40$  m.y. upper intersect and of  $1,250 \pm 90$  m.y. lower intersect. The 3,560 m.y. number is believed by Peterman and coworkers to be a minimum age because analysis of one of the least discordant zircon

fractions by ion microprobe by Australian workers gave a nearly concordant age of 3,650 m.y. The 1,250-m.y. lower intersect is without geological significance: it is interpreted to be a result of multiple lead loss at 2.7, 1.8, and 0.5 Ga. Late Archean amphibolites in the dome are dated at 2.64 Ga by U-Pb in zircon. Archean rocks 10–25 km northwest of the Watersmeet dome, however, give a 2.75 Ga age on zircons. Quartz monzonite here is dated at 2.65 Ga. These late Archean metavolcanic and plutonic rocks presumably lie at the southern margin of the Wawa greenstone-granite terrane.

C.D. Frost, B.R. Frost, M.E. Koesterer, T.P. Hulsebosch and D. Bridgwater gave their preliminary results on Archean rocks of the Wind River Mountains, Wyoming. Though the southern half of this range is formed of late Archean granitic rocks, the northern half contains much older orthogneiss and migmatite. Work in progress in the Medina Mountain area on migmatitic metasedimentary gneisses, mafic gneisses and minor iron-formation, ultramafic rocks and calc-silicate rocks shows: a large synformal structure; felsic garnet gneiss as a partial melt of metasedimentary protolith; successive injection by granite, basalt and tonalite, and lastly, granodiorite and granite; and at least two major metamorphic events at or close to granulite facies (at 5–6.5 kb and as hot as 800°C). Medina Mountain supracrustals give a 3.4 Ga model Nd age. The nearby Bridger batholith gives an Rb-Sr age of 2.75 Ga and a crustal residence age by Nd isotopes of ca. 2.9 Ga. Frost and her coworkers stress that the northern part of the Wind River Mountains contains an extensive pre-2.7 Ga history and that this terrane is one *not* having extensive tonalitic-trondhjemitic gneisses.

A.K. Gibbs and K.R. Wirth summarized the nature and temporal development of the Amazonian Craton. This craton, roughly 1,000 by 3,000 km, is divided into four terranes: (1) the Imataca Province, a complex of gneisses and sedimentary rocks as old as 3.4 Ga and metamorphosed at 2.7 Ga; (2) the Northern Granite-Greenstone Terrane, developed at 2.25–2.1 Ga; (3) the Central Guiana Granulite Belt, a poorly known terrane of paragneiss, orthogneiss, quartzite, marble and other rocks; and (4) the Para province of Brazil, consisting of gneiss complexes, greenstone belts, iron formation of 2.8–2.7 Ga, and overlying clastic rocks. All four terranes are overlain by 1.9–1.65 Ga age sediments and volcanics and were intruded by the Paraguayan granitic rocks at 1.55–1.45 Ga. Gibbs and Wirth emphasized that greenstone belts otherwise identical to those of Archean age of other cratons give both U-Pb zircon and Sm-Nd ages of 2.3–2.1 Ga.

F. Barker presented a poster display of a well-exposed, 3-km-thick layer of Cretaceous amphibolite north of Yakutat, Alaska that was partially melted to high- $\text{Al}_2\text{O}_3$  trondhjemite pegmatite. This occurrence is significant, especially in regard to Archean petrogenesis, in that the melting of about 10% of hornblende-plagioclase-epidote-quartz-sphene amphibolite occurred (apparently at high  $2\text{H}_2\text{O}$ ) without development of either pyroxene or garnet. Furthermore, the heavy REE's are strongly depleted, Eu shows a positive anomaly (resulting from equilibration of liquid with hornblende), and La is the rare earth element more abundant in the trondhjemite than in the residuum. Thus these rocks at Yakutat give excellent evidence that garnet-free and pyroxene-free amphibolite, indeed, may partially melt to produce trondhjemitic liquid.

## DISCUSSION OF FIELD EXCURSION TO AMERALIK FJORD

### Kangimut sangmissoq Gneiss - Amîtsoq or Nûk Equivalents?

by

Carol D. Frost and Alan M. Goodwin

At a locality on the south shore of Ameralik fjord, 40 km southeast of Nuuk/Godthåb in West Greenland, rocks that have clearly been retrogressed from late Archean (2800 Ma) granulite facies have the field characteristics of early Archean (3400 Ma) Amîtsoq gneiss with Ameralik dikes (3400–3100 Ma), yet have Rb-Sr, Pb-Pb and Sm-Nd characteristics that indicate derivation from a mantle source in the late Archean (3100–2900 Ma). Are the field or the isotopic characteristics being misjudged in this case, and how can the problem be resolved? This is perhaps the most fundamental problem to emerge from the field workshop.

The West Greenland Archean gneiss complex centered around Godthåbsfjord and extending from Isukasia in the north to south of Færingehavn has been particularly significant to our understanding of early crustal genesis. The combination of excellent exposure over an extensive area, relatively detailed geological mapping of much of the region, and a considerable volume of high quality isotopic and other geochemical data give special insight into processes that operated at moderately deep crustal levels in the Archean. Of emerging interest is the effect of granulite facies metamorphism on these Archean rocks, especially the extent to which chemical, and therefore isotopic systems were disturbed. Similar metamorphic processes may have disrupted geochemical evidence for ancient crust in other high grade terrains. If so, then an understanding of the chemical effects of granulite

metamorphism at the Kangimut sangmissoq locality on Ameralik fjord has importance not only for studies of crustal evolution in West Greenland, but also for the problem of ancient crust preservation worldwide.

The components which may comprise the gneisses at Kangimut sangmissoq are: Amîtsoq gneiss, Ameralik dikes and/or Nûk gneiss. These components were recognized and defined in the Godthåbsfjord area by V.R. McGregor and associates of the Greenland Geological Survey over the last twenty years. It was established that an older complex of rocks in the Godthåbsfjord region, subsequently called Amîtsoq gneiss, was distinguished from younger seemingly identical rocks, called Nûk gneiss, on the basis of a single field criterion, namely the presence in Amîtsoq gneiss of abundant tabular bodies of amphibolite derived from mafic dikes to which the name Ameralik dikes was given. Significantly, amphibolites derived from basic dikes are rare to absent in lithologic units of other ages in the region. Subsequent isotopic studies showed that the gneiss units with abundant Ameralik dikes were all formed in the 3800–3400 Ma age interval.

Most Amîtsoq gneiss is highly deformed, and original discordant contacts between different phases have been erased and individual bodies thinned. Very little of the Amîtsoq gneiss retains its primary character. Granulite facies mineral assemblages resulting from metamorphism at ca. 3.6 Ga are preserved in a number of localities off the coast near Buksefjorden. This 3.6 Ga granulite grade metamorphism may have affected the Kangimut sangmissoq area; however, later granulite metamorphism has obliterated any field evidence of this early event.

Ameralik dikes, the abundant tabular bodies of massive, homogeneous amphibolites derived from mafic dikes emplaced in Amîtsoq gneiss, occur every few meters or tens of meters across strike in most outcrops of early Archean rocks. Most Ameralik dikes, which were intruded during the interval 3.4 to 3.1 Ga, are less than 2 m thick. The contacts have been rotated by intense deformation into concordance with the layering of the enclosing rocks. A small proportion of Ameralik dikes contain white plagioclase clots that, in some of the least modified dikes, are thought to be derived from euhedral megacrysts of calcic plagioclase. These white clots are used as a field indicator of Ameralik dikes. Amphibolite bodies bearing plagioclase clots are found at Kangimut sangmissoq.

The term Nûk gneiss is applied to all quartzofeldspathic gneiss that does not contain Ameralik dikes and that intrudes and migmatizes Amîtsoq gneiss and associated rocks. The type Nûk gneisses give U-Pb zircon dates of 3.1 to 2.9 Ga for various phases. After Nûk gneiss emplacement the region was affected by a complex and as yet imperfectly understood sequence of deformation,

metamorphism and intrusion. Granulite facies metamorphism occurred at ca. 3.0 Ga under conditions calculated at 800°–850°C and 7–9 kb, and again at ca. 2.8 Ga when rocks affected by this late Archean metamorphism were strongly depleted in U, Th, Rb and K. Evidence for the 2.8 Ga granulite grade metamorphism is present within inner Ameralik and Færingehavn fjord, including at the Kangimut sangmissoq locality.

The above provides the background for the problem gneisses at Kangimut sangmissoq. The field evidence in favor of dominantly early Archean Amitsoq gneisses at this locality is based upon the observation that the Kangimut sangmissoq gneisses enclose abundant tabular bodies of amphibolite that have the field characteristics of Ameralik dikes. A number of these amphibolites contain trains or clots of calcic plagioclase. Relict cores in a thick body of well-layered rock with abundant large plagioclase clots preserve granulite facies mineral assemblages. These abundant amphibolite bodies are identical to Ameralik dikes in the type Amitsoq gneisses only 10 km to the west. The obvious differences between the type Amitsoq gneisses and the gneisses at Kangimut sangmissoq are: (1) that the latter were subjected to late Archean granulite facies metamorphism and subsequently retrogressed to amphibolite facies, whereas the type Amitsoq gneisses were not metamorphosed above amphibolite facies in the same period, and (2) the Kangimut sangmissoq gneisses are enclosed in and probably to some extent penetrated by Nûk gneisses.

The isotopic data from Kangimut sangmissoq is extensive, and has yielded the following: a six whole rock sample Rb-Sr isochron yielding a date of  $2700 \pm 185$  Ma with an initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of 0.70195; a six whole rock sample Sm-Nd isochron giving a date of  $2825 \pm 125$  Ma and an initial  $^{143}\text{Nd}/^{144}\text{Nd}$  ratio of 0.50918; 18 whole rock Pb-Pb samples indicating derivation mainly from a juvenile source at ca. 2.8 Ga with some samples showing evidence for contamination with Amitsoq-type Pb; and zircons from one gneiss sample falling on the Akilia association zircon U-Pb discordia. These isotopic characteristics are similar to those for Nûk gneisses, hence the conflict with field evidence.

We consider that the root of the Kangimut sangmissoq problem lies in overextending the available field and isotopic data. On the one hand, the field data are limited in terms of the ability to confidently identify Ameralik dikes and hence Amitsoq gneiss to the exclusion of all younger dikes and gneiss, especially so in this complexly deformed region where stratigraphic continuity between adjoining outcrops must remain uncertain no matter how close their proximity. On the other hand, our limited understanding of element mobility during granulite facies metamorphism, especially repeated metamorphisms, does

not permit an irrefutable interpretation of the isotopic systematics of these rocks. One approach to the problem is to repeat the isotopic analyses on presumed Amitsoq gneisses elsewhere that have not been subjected to late Archean granulite metamorphism. If a significant Nûk component is indicated in this second locality, then one would conclude that the Kangimut sangmissoq isotope systematics need not be explained in terms of element redistribution during metamorphism.

A more satisfactory approach lies in the extensive study of high grade metamorphic processes and chemical mobility associated with those processes. Despite well documented chemical depletion associated with granulite metamorphism, some granulite areas show variable, little, or no depletion of LIL and REE. This is probably a reflection of the fact that granulite metamorphism may be the result of more than one petrologic process. Prominent among proposed mechanisms are the influx of  $\text{CO}_2$  which may be capable of transporting LIL elements and REEs, or crustal melting in which the melt extracts the elements necessary to account for the observed depletion. Studies are needed in many different granulite terrains before element mobility expected during a certain metamorphic process can be well quantified.

A pressing need in West Greenland is for detailed metamorphic petrology especially in areas such as Kangimut sangmissoq. Studies should include documentation of mineral assemblages, textures, and reactions that buffer the fluids present, in order to estimate reliably temperatures and pressures and the metamorphic conditions in each locality. Knowing more about the metamorphic processes having taken place, for example, at Kangimut sangmissoq, it may be possible to calculate the degree of element depletion expected via that process and to compare those figures to the chemical mobility required to generate Nûk-like isotope systematics from an Amitsoq gneiss. At present, we do not have the knowledge of metamorphic processes and partition coefficients of various elements into various metamorphic fluids to perform such a calculation. But if the controversy generated at Kangimut sangmissoq serves to spur ambitious research programs along these lines, then our present frustration with a currently unresolvable problem will have served a very valuable purpose.

# ABSTRACTS

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SPECULATIONS ON NATURE AND EXTENT OF ARCHEAN BASEMENT IN LABRADOR  
AS INDICATED BY SR, ND, AND PB ISOTOPIC SYSTEMATICS OF PROTEROZOIC INTRUSIVES.

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Introduction. Sm-Nd and Rb-Sr isotopic compositions of mid-to late Proterozoic ( $\sim 1.6$ -1.1 Ga) massif-type anorthosites and mafic intrusives in the eastern Canadian shield are correlated with geographic location (1,2). Complexes in the Grenville province have positive  $\epsilon_{\text{Nd}}$  values and initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ( $I_{\text{Sr}}$ ) generally less than 0.703, suggesting derivation from depleted mantle. In Labrador, similar complexes close to or northwest of a line roughly corresponding to the Grenville Front have negative  $\epsilon_{\text{Nd}}$  values and  $I_{\text{Sr}} > 0.703$ . This contrast has been interpreted as reflecting either enriched mantle under the Nain Province (1), or contamination of the Nain intrusives with older crustal components (2). Pb isotopic compositions, however, favor the latter (3). We speculate here on the possibility of using these Proterozoic intrusives as tracers to characterize the nature and extent of older basement types in Labrador.

Harp Lake and Mealy Mountains Complexes. Our data base includes Sr, Nd, and Pb isotopic compositions of 1.6-1.65 Ga anorthosites and related rocks from the Harp Lake (Nain Province) and Mealy Mountains (Grenville Province) complexes, and also of later ( $\sim 1.4$  Ga) mafic dikes which crosscut them (Fig. 1) (3-6). The anorthosite complexes are large (7000-8000 km<sup>2</sup>) composite massifs dominated by leucotroctolites and leuconorites, with minor ferrodiorites and gabbros (4). Both complexes are crosscut by an ENE-trending swarm of olivine diabase dikes with similar mineralogy and major and minor element chemistry (5,6). Mealy dikes yield a whole-rock Rb-Sr age of  $1380 \pm 54$  Ma (Fig. 2) (6). Harp and Mealy dikes have been suggested as correlative with other gabbroic rocks of similar age in Labrador, including the Shabogamo, Michael, and Flowers River gabbros, the Seal Lake volcanics, and the Kiglapait layered intrusion (5,6).

Mealy anorthosites have  $I_{\text{Sr}} = 0.7026 - 0.7032$  and  $\epsilon_{\text{Nd}} = +1.2$  to +3.0 (computed for 1.65 Ga). Mealy dikes have  $I_{\text{Sr}} = 0.7025 - 0.7028$  and  $\epsilon_{\text{Nd}} = +3.8$  to +5.6 (computed for 1.4 Ga). Both are consistent with derivation from mantle sources depleted with respect to Rb/Sr and Nd/Sm. Pb isotope data for Mealy anorthosites and dikes form a linear array between the evolution curves for model mantle (7) and average crust (8). This array is essentially equivalent to that for Proterozoic carbonatites, which Tilton (9) interpreted as reflecting depleted mantle.

Harp Lake samples show a much larger variation in isotopic composition (Figs. 2, 3). The major rock units of the Harp Lake anorthosite complex have  $I_{\text{Sr}}$  between 0.7039 and 0.7066, and  $\epsilon_{\text{Nd}}$  between -2.4 and -6.0 (at 1.65 Ga). Harp dikes have  $I_{\text{Sr}} = 0.7032 - 0.7033$  and  $\epsilon_{\text{Nd}} = -0.3$  to -2.3 (at 1.4 Ga). The Nd isotopic data for Harp dikes show a narrow range of  $^{147}\text{Sm}/^{144}\text{Nd}$  (0.146 - 0.153), but plot along a  $\sim 3.3$  Ga reference line, probably reflecting mixing with an Archean component (Fig. 3). Harp Lake anorthosites and related rocks show a wide scatter in Pb isotope compositions, and can be interpreted as reflecting mixing between a depleted Proterozoic mantle component and an older component with extremely unradiogenic Pb.

Likewise, Harp dikes and plagioclase separates therefrom have very low  $^{207}\text{Pb}/^{204}\text{Pb}$  for Proterozoic mantle-derived materials, and must be interpreted as reflecting contamination with U-depleted crustal material.

Possible Contaminants. Although we cannot constrain the precise nature of the contaminant, its composition must be such that it has essentially no effect on the major or minor element chemistry of Harp Lake samples, assuming that Mealy Mountains samples can be considered uncontaminated starting materials. Harp dikes show no noticeable enrichments in "crustal" components such as  $\text{SiO}_2$ ,  $\text{K}_2\text{O}$ ,  $\text{Na}_2\text{O}$ , etc. The most appropriate contaminant would have sufficiently low  $\text{Rb}/\text{Sr}$ ,  $\text{Sm}/\text{Nd}$ , and  $\text{U}/\text{Pb}$  such that its isotopic compositions evolve to relatively low values of  $^{87}\text{Sr}/^{86}\text{Sr}$ ,  $^{143}\text{Nd}/^{144}\text{Nd}$ , and  $^{207}\text{Pb}/^{204}\text{Pb}$  by about 1.4 Ga.

The Harp Lake complex, and other Proterozoic intrusives in the Nain Province of Labrador were emplaced near the boundary between Aphebian (1.7 - 1.8 Ga) gneisses of the Churchill Province, and a belt of Archean gneisses with ages as old as 3.6 Ga, exposed along the eastern coast of Labrador (Fig. 1) (4,10). The Aphebian gneisses are considered to be reworked equivalents of late Archean ( $\sim 2.7$  Ga) materials similar to those in the Superior Province (11), and the older Archean gneisses of coastal Labrador have been correlated with the ancient gneiss terrane of West Greenland (e.g. 10).

Initial Sr and Nd isotopic compositions (at 1.4 Ga) of these gneisses are compared with those of Harp and Mealy dikes in Fig. 4. Data for the Churchill and Superior Provinces are McCulloch and Wasserburg's (11) composites for large areas of these terranes. The wide range in isotopic composition among Uivak gneisses is a likely consequence of early granulite facies metamorphism which produced low  $\text{Rb}/\text{Sr}$  and  $\text{I}_{\text{Sr}}$  in some areas (12,13). Among these possibilities, the most suitable contaminant for the Harp dikes would be Rb-depleted Uivak gneiss (component B, Fig. 4). Less than 10% of such a component added to Mealy dikes would produce the isotopic composition of the Harp dikes, assuming simple two-component mixing (Fig. 4). Although the Superior and Churchill Province composites would not appear to be appropriate contaminants, we cannot rule out as a possibility a Rb-depleted equivalent of such material, produced for example, by granulite facies metamorphism (component C, Fig. 4). This hypothetical component would be a less satisfactory contaminant in that it would require a larger degree of contamination (15 - 25%). Pb isotope systematics also favor an ancient gneiss-type contaminant (Uivak or Amitsoq gneiss) over late-Archean gneisses (Fig. 5).

Discussion. Although it remains speculative, it could be inferred from our data that the ancient gneiss complex exposed along coastal Labrador extends in the subsurface, beneath the Harp Lake anorthosite complex, and possibly as far west as the Labrador Trough, where the 1.45 Ga Shabogamo gabbros also have negative  $\epsilon_{\text{Nd}}$  values of about -5 (14). Pb isotopic compositions of these, and other mafic intrusives in Labrador are clearly needed to evaluate this. It is possible, therefore, that the Archean North Atlantic craton is much more extensive than indicated by present surface exposures.

In any case, Proterozoic intrusives in the Grenville Province show no evidence of contamination with Archean crustal components. The Labrador segment of the Grenville Front, therefore, appears to mark the southern edge of the Archean craton in eastern North America. It is possible that this feature coincides with a suture, but if this is the case, it must be older than 1.6 Ga.



Fig. 1

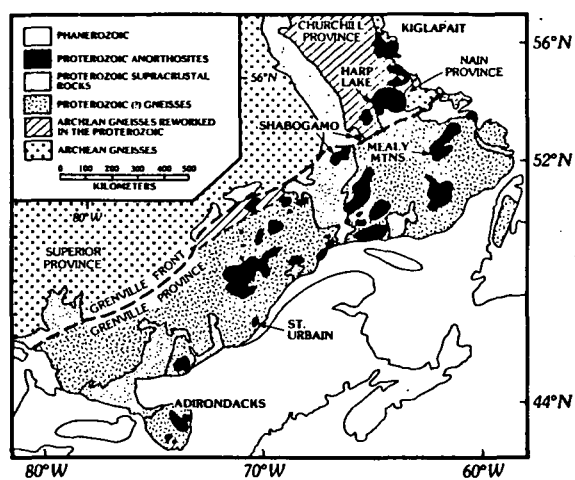


Fig. 2

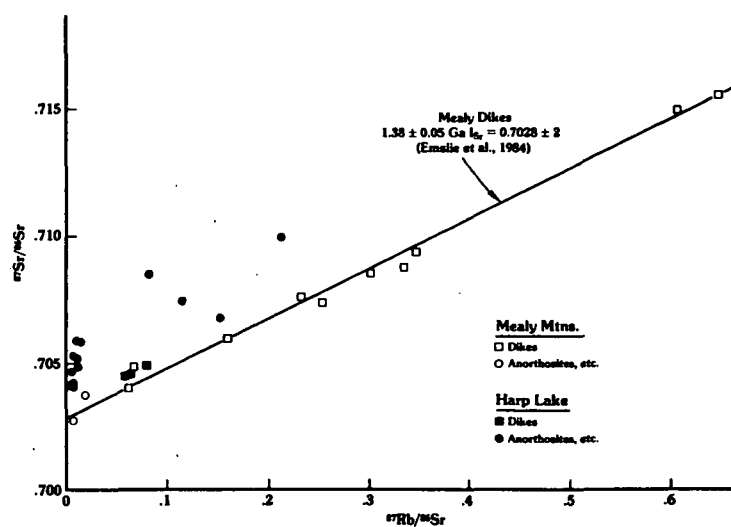
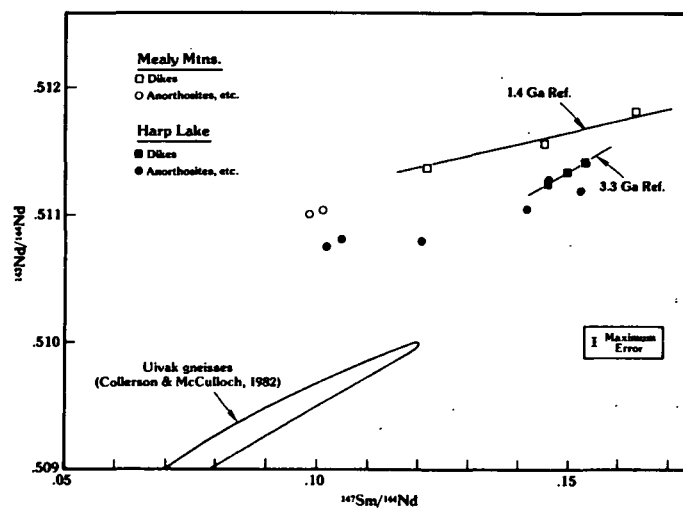
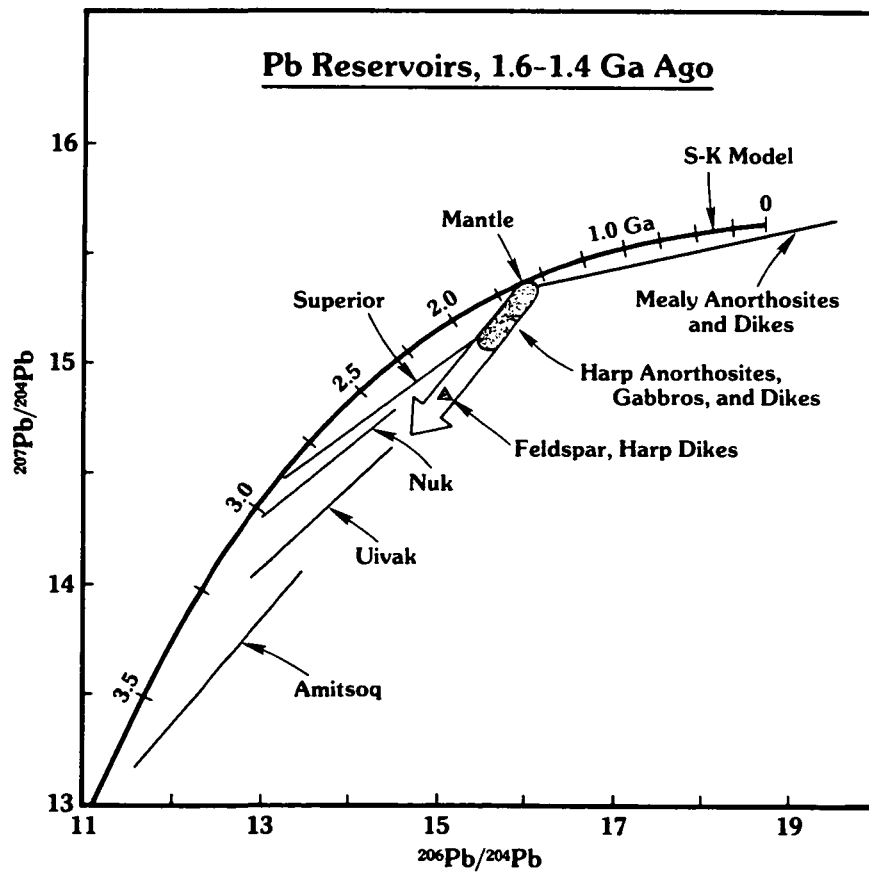
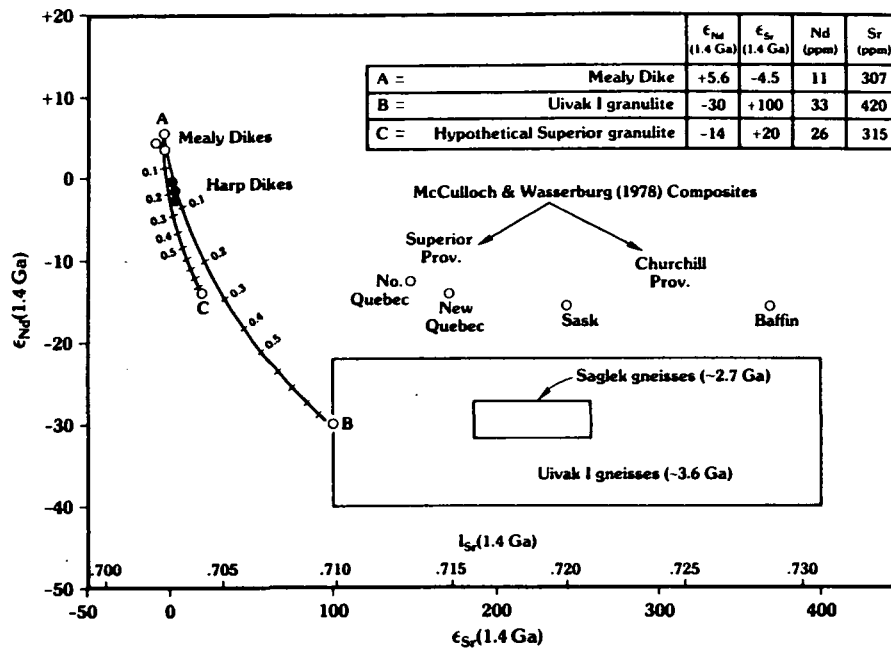


Fig. 3





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PARTIAL MELTING OF AMPHIBOLITE TO TRONDHJEMITE NEAR YKUTAT, ALASKA  
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At Nunatak Fiord, 55km NE of Yakutat, Alaska, a uniform layer of Cretaceous metabasalt ca. 3 km thick was metamorphosed to amphibolite facies and locally partially melted to trondhjemite pegmatite. A region of melting ca. 1 km broad (normal to foliation and layering) fades into unmelted amphibolite (a feature resulting from ingress of aqueous fluid from below?). Segregations of plagioclase-quartz±biotite rock, all presumed to be melt, range in size from stringers several mm thick to blunt pods as much as 6m thick. The ratio of melt/residuum is 5-10%. The assemblage aluminous hornblende-plagioclase (An<sub>34-49</sub> in grain-to-grain variation)-epidote-sphene-quartz gave a water-saturated melt that crystallized to plagioclase(An<sub>23-28</sub>)-quartz-biotite trondhjemite pegmatite. Only one generation of melt is present. The pegmatite segregations tend to be parallel to foliation of the amphibolite, but crosscutting relations are common. Deuteric or late-magmatic quartz seams 1-5mm thick are marginal to many trondhjemite pods.

The amphibolite's protolith was light-REE-depleted oceanic tholeiite of 48.3% SiO<sub>2</sub>, 15.3% Al<sub>2</sub>O<sub>3</sub>, 10.7% FeO\*, 8.4% MgO, 12.6% CaO, 2.27% Na<sub>2</sub>O, 0.08% K<sub>2</sub>O, 0.72% TiO<sub>2</sub>, <0.05% P<sub>2</sub>O<sub>5</sub>, 0.19% MnO, 53ppm Sc, 320ppm Cr, 110ppm Ni, 2ppm Rb, 71ppm Sr, 22ppm Y, 41ppm Zr, <5ppm Nb, 18ppm Ba, and La 3X, Sm 8X, and Lu 12X chondrites. There is no Eu anomaly. Loss/gain of mobile elements by postmagmatic processes cannot be assessed, but probably is minor. The trondhjemite pegmatite shows 75.3% SiO<sub>2</sub>, 15.7% Al<sub>2</sub>O<sub>3</sub>, 0.41% FeO\*, 0.29% MgO, 3.51% CaO, 5.01% Na<sub>2</sub>O, 0.32% K<sub>2</sub>O, 0.04% TiO<sub>2</sub>, <0.05% P<sub>2</sub>O<sub>5</sub>, <0.02% MnO, <5ppm each Sc, Cr, Ni and Nb, 54ppm Rb, 232ppm Sr, 2ppm Y, 506ppm Ba, and La 6X, Sm 0.4X, Gd-Tm 0.3X and Lu 0.7X chondrites. Eu at 2X chondrites shows a strong (+) anomaly. (REE analyses by group separation and activation.) REE partitioning in residuum/melt is even more pronounced than that discussed by Arth and Barker (1976), especially in view of the involvement of sphene and epidote.

Melting of garnet-free amphibolite to give heavy-REE-depleted (relative to residuum) trondhjemitic melt seems to be a viable process.

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GEOCHEMISTRY OF GRANITOID ROCKS FROM THE WESTERN SUPERIOR PROVINCE - EVIDENCE FOR 2- AND 3-STAGE CRUSTAL EVOLUTION MODELS; G.P. Beakhouse, Precambrian Geology Section, Ontario Geological Survey, 77 Grenville St. 64910643  
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The Superior Province is divisible into subprovinces that can be classified as greenstone-tonalite, paragneiss or batholithic terranes and are distinguished by differences in lithologic proportions, metamorphic grade and structural style [1]. This paper discusses the origin and significance of contrasting geochemical characteristics of plutonic rocks from the Winnipeg River subprovince (a batholithic terrane) and the Wabigoon subprovince (a greenstone-tonalite terrane).

In the western Wabigoon subprovince well preserved, low- to medium metamorphic grade supracrustal sequences, in which metavolcanic rocks predominate over metasedimentary rocks, are deformed into arcuate belts which wrap around elliptical granitoid batholiths [2]. This volcanism and plutonism took place over a restricted time interval between 2700 and 2750 Ma [3, 4, 5]. The batholiths are composite, consisting of; 1) foliated to gneissic, tonalitic to granodioritic diapirs and 2) later, massive to foliated dioritic to granitic plutons [6].

The Aulneau batholith was selected as an example of a greenstone-tonalite terrane batholith. Ziehlke [7] recognizes 19 phases which can be broadly grouped in order of decreasing relative age as early migmatitic phases, hornblenditic and/or biotitic foliated phases and late massive phases. Tonalitic to granodioritic compositions predominate and there is a general trend of decreasing colour index and increasing microcline abundance with decreasing relative age [7]. The Aulneau batholith displays limited chemical heterogeneity reflecting relatively uniform mineralogy. Noteworthy geochemical characteristics include (averages in brackets); high  $\text{Na}_2\text{O}$  (5.4%), Sr (690 ppm) and low  $\text{K}_2\text{O}$  (1.6%), Rb (54 ppm), Ce (26 ppm), La (14 ppm) and Y (2 to 3 ppm). These characteristics are typical of Early Precambrian tonalites [8] and have been widely interpreted to reflect an origin involving partial melting of tholeiitic basalt at mantle or lower crustal depths [8, 9, 10, 11, 12].

The Winnipeg River batholithic terrane is underlain principally by variously deformed and recrystallized plutonic rocks including: 1) pre-tectonic, heterogeneous gneissic complexes, 2) pre- to syn-tectonic sodic plutons and 3) syn- to post-tectonic potassic plutons [13]. The gneissic complex and some of the sodic plutons range in age from 2830 Ma to 3168 Ma [14, 15, 16] and are significantly older than Wabigoon subprovince volcanism and plutonism. The potassic plutons range in age from 2660 to 2700 Ma [15]. Inclusions of supracrustal rocks are predominantly of volcanic origin and underlie less than 10 percent of the terrane but are widely distributed. Metamorphic grade is upper amphibolite to granulite facies and evidence of in situ partial melting is common in the supracrustal inclusions and gneissic complex.

The youngest regional tectonic deformation, involving the development of nappe-like structures and subsequent doming of tectonically thickened crust, occurred between 2710 and 2702 Ma [16].

Two distinct geochemical affinities are recognized within the plutonic rocks of the Winnipeg River subprovince. The heterogeneous gneissic complex and sodic plutons are predominantly of tonalitic composition; they are

characterized by low LIL element abundances, depleted HREE and low initial Sr isotopic composition and are interpreted to be the product of 10 percent melting of a mafic garnet granulite of tholeiitic basalt composition [17, 18]. Potassic plutons range in composition from granodiorite to granite and are more geochemically evolved than the tonalitic rocks. For example, compared to the Aulneau batholith, the Lount Lake potassic batholith has higher  $K_2O$  (3.8%), Rb (116 ppm), Ce (53 ppm), La (53 ppm) and Y (11 ppm) and lower  $Na_2O$  (4.3%) and Sr (415 ppm). Other potassic plutons in the Winnipeg River belt (e.g. the Lac du Bonnet pluton [19]) are even more geochemically evolved. The initial Sr isotopic composition of granodioritic phases from the Lount Lake batholith range from .7022 to .7044 [15]. The following suggest potassic plutons are derived from the partial melting of the earlier tonalites:

- 1) LIL element mass balance requirements are consistent with derivation of the potassic plutons by partial (<50%) melting of tonalite. A tholeiitic basalt source would require unrealistically low degrees of partial melting (1-2%).
- 2) Y abundance in potassic plutons is highly variable but in general they are comparable to or greater than abundances in potential source rocks suggesting that it is unlikely that significant garnet or amphibole was retained in the source material. Felsic rocks are more likely to satisfy this requirement than mafic rocks.
- 3) The initial Sr isotope ratios of the potassic plutons are similar to those expected in the older tonalites at the time of potassic plutonism [15] and are more radiogenic than would be expected for 3.0 to 3.2 Ga tholeiitic basalt [20].
- 4) Pods of in situ melt rocks observed in the older tonalites have geochemical characteristics that resemble those of the potassic plutons.

The geochemical diversity of the Winnipeg River terrane can be interpreted in terms of a 3-stage magma evolution model, the first two stages of which are identical to that proposed for greenstone-tonalite terranes.

Stage I - Partial melting of the mantle to produce tholeiitic basalt

Stage II - Partial melting of tholeiitic basalt to produce magmas of tonalitic affinity.

Stage III - Partial melting of the bi-modal assemblage formed in stages I and II to produce the potassic plutons.

Possible implications of this model include: 1) The paucity of potassic plutons suggests that a Winnipeg River type basement complex is thin or absent beneath the Wabigoon subprovince. 2) The lower crust beneath the Winnipeg River and Wabigoon terranes may be different with the former being depleted as well as dehydrated. 3) Sialic microcontinents, parts of which are as old as 3.0-3.2 Ga, were present in the Superior province prior to widespread volcanism and plutonism which took place between 2700 and 2800 Ma.

Synchronous (2710-2700 Ma) cessation of volcanism in the Wabigoon subprovince and tectonic thickening and initiation of extensive crustal anatexis in the Winnipeg River subprovince suggests that the late history of these terranes is related. This is interpreted within a plate tectonic model to reflect the docking of a volcanic arc (Wabigoon subprovince) against a craton lying to the north of it. This led to the cessation of subduction and volcanism in the Wabigoon subprovince and tectonic thickening in the Winnipeg River subprovince with the latter resulting in extensive crustal anatexis that generated the potassic plutons. Local unconformable



relationships along the Wabigoon-Winnipeg River interface are a consequence of late sequences within the Wabigoon lapping on to the Winnipeg River terrane prior to and during collision.

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GEOLOGY AND TECTONICS OF THE ARCHEAN SUPERIOR  
PROVINCE, CANADIAN SHIELD;  
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Although it is the world's largest relatively undisturbed region of Archean crust, Superior Province is only a remnant of a formerly more extensive craton. It is transected and surrounded by Early Proterozoic orogens which display lithological and tectonic zonation consistent with the operation of plate tectonic processes (Hoffman et al., 1982).

Superior Province has high-grade gneiss regions in the north (Pikwitonei, Minto) and south (Minnesota River Valley) characterized by granulite facies gneiss and abundant plutonic rocks. One of these (MRV) has rocks older than 3.5 Ga; absolute ages of Pikwitonei and Minto rocks are unknown but Minto does have north-south structural trends distinctive from the dominant east-west structures of the rest of Superior Province.

Between the northern and southern high-grade gneiss regions are alternating east-west trending subprovinces whose supracrustal components are dominated by metavolcanics or by metasediments. Metavolcanic-rich subprovinces (Abitibi, Wabigoon etc.) are characterized by sinuous, upright, low-grade (subgreenschist to amphibolite facies) komatiitic, tholeiitic, calc-alkalic and rare alkalic volcanic sequences with volcanogenic clastic and chemical sediments. Most metavolcanic belts consist of several lensoid, overlapping volcanic piles each on the order of 100 km in maximum dimension and approximately 10 km thick. Each volcanic pile comprises several volcanic cycles consisting of a lower komatiitic-tholeiitic basalt sequence, a middle tholeiitic basalt-andesite-dacite sequence, and an upper calc-alkalic dacite-rhyolite-andesite-basalt sequence. Chemical (iron formation, chert) and clastic (wacke, conglomerate) sediments occur within and between the volcanic cycles and, to a limited extent, as marginal aprons about the volcanic edifices. In terms of rock types, sequences, and overall configuration, Archean metavolcanic belts are most closely analogous to modern island arcs (Goodwin, 1977).

The intervening metasedimentary belts (Quetico, Pontiac, etc.) consist mainly of turbiditic wacke and pelite metamorphosed at grades ranging from low greenschist at belt margins to upper amphibolite, and locally granulite, in belt interiors. Metasedimentary subprovinces have a deceptively simple "straight" structural aspect due to strongly developed foliation, subhorizontal isoclinal folds, and gently plunging lineation. These, however, are late structures overprinted on earlier complex recumbent folds and dome and basin structures. Although data are lacking on their age, it is possible that the metasediments are broadly correlative with the adjacent metavolcanic sequences. Hence, they may represent dominantly volcanogenic detritus deposited in inter-arc sedimentary basins.

Plutonic rocks are particularly abundant in Superior Province; several subprovinces (Berens River, Winnipeg River, etc.) consist almost exclusively of felsic and intermediate plutons and orthogneiss. Plutonic rocks in the volcano-plutonic subprovinces include tonalitic gneiss, synvolcanic quartz diorite, trondhjemite and granodiorite plutons, younger granodiorite batholiths, and still younger granitic and syenitic intrusions. Peraluminous S-type granites are common

in the high-grade migmatitic parts of the metasedimentary subprovinces. Some early plutonic units may represent pre-volcanic sialic basement, but unconformable relationships can rarely be demonstrated. For the most part, the earliest plutonic rocks intrude the supracrustal rocks and commonly contain abundant, locally-derived xenoliths. The tonalitic and mafic gneisses are characterized by domal structures, in part attributable to diapirism and in part to polyphase deformation involving thrusting and recumbent folding.

U-Pb zircon dates demonstrate that volcanic, plutonic, deformational and metamorphic events of relatively brief duration were essentially synchronous over large parts of Superior Province but that there are detectable differences in ages of events from one area to another (Krogh et al., 1982). In the north (Uchi, Sachigo) major volcanism and plutonism occurred between 3.0 and 2.8 Ga and again between 2.75 and 2.7 Ga. Major deformation and metamorphism at about 2.73 to 2.7 Ga were accompanied and followed by plutonism. In the south (Abitibi, Wawa, Wabigoon) major volcanism and plutonism occurred at about 2.75 to 2.79 Ga. Here, deformation and metamorphism of the supracrustal sequences at about 2.68 to 2.7 Ga were accompanied and followed by plutonism at 2.7 to 2.66 Ga.

Dextral transcurrent faults trending EW and NW and sinistral faults trending NE form subprovince boundaries in part, as do NE and EW trending thrusts. The most notable product of the thrust faulting, the Kapuskasing structural zone, exposes granulites considered to represent lower crust brought to surface by movements on crustal-scale faults that transect the east-west trending subprovinces (Percival and Card, 1983).

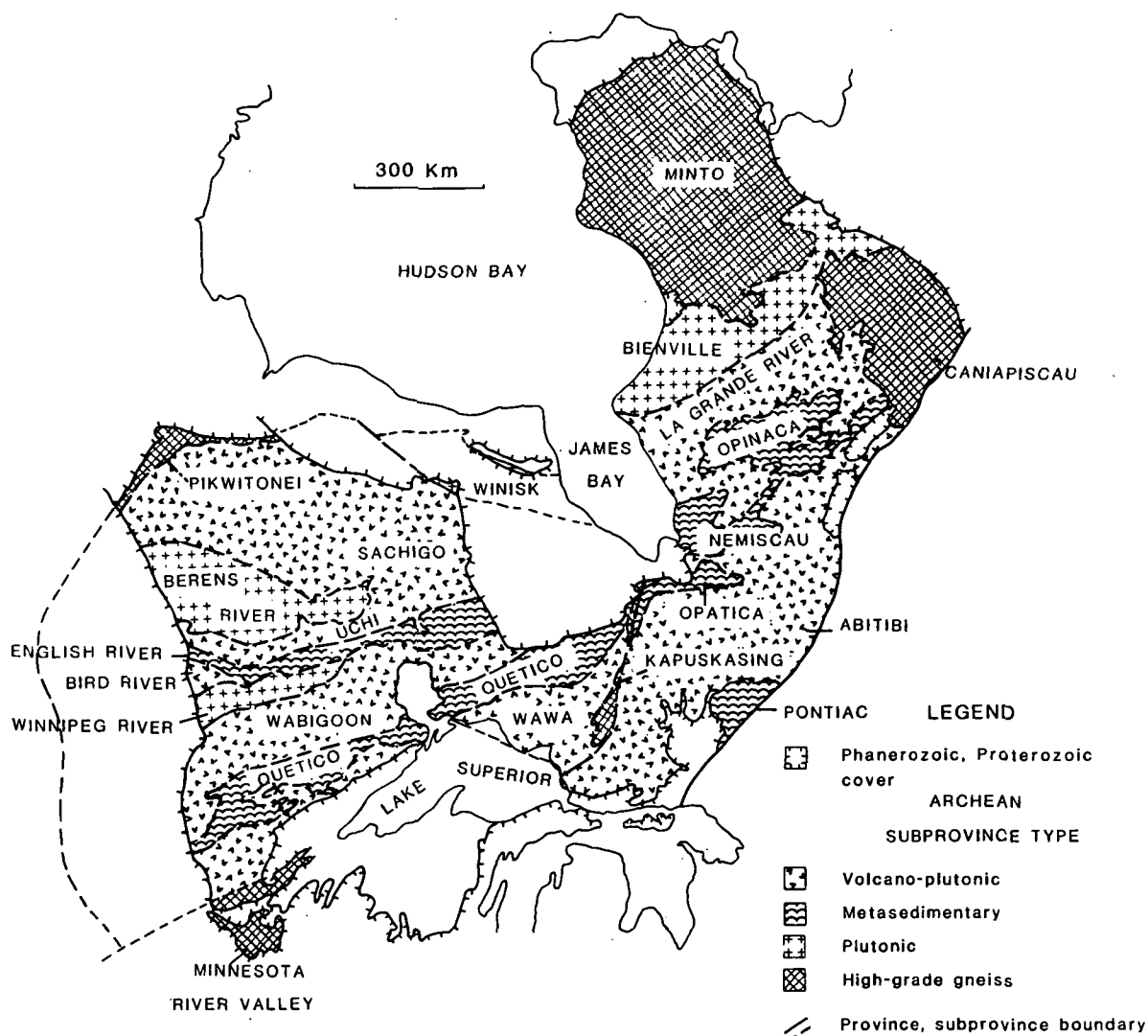
In summary, Superior Province consists mainly of Late Archean rocks with Middle Archean gneisses in the south, and possibly the north. The Late Archean supracrustal sequences are of island arc and inter-arc affinity and are cut by abundant plutonic rocks, including early arc-related intrusions, late synorogenic intrusions, and post-orogenic plutons that are possibly the product of crustal melting caused by thermal blanketing of newly-thickened continental crust combined with high mantle heat flux. The contemporaneity of magmatic and deformational events along the lengths of the belts is consistent with a subduction-dominated tectonic regime for assembly of the Kenoran Orogen. Successive addition of volcanic arcs accompanied and followed by voluminous plutonism resulted in crustal thickening and stabilization of the Superior craton prior to uplift of Kapuskasing granulites, emplacement of the Matachewan diabase dykes, and Early Proterozoic marginal rifting.

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STRONTIUM AND NEODYMIUM ISOTOPIC VARIATIONS IN EARLY ARCHEAN GNEISSES  
AFFECTED BY MIDDLE TO LATE ARCHEAN HIGH-GRADE METAMORPHIC PROCESSES: WEST  
GREENLAND AND LABRADOR. K.D. Collerson<sup>1,5</sup>, M.T. McCulloch<sup>1</sup>, D. Bridgwater<sup>2</sup>,  
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Introduction. Relicts of continental crust formed more than 3400 Ma  
ago are preserved fortuitously in most cratons. They provide the most direct  
information about crust and mantle evolutionary processes during the first  
billion years of Earth history. In view of their polymetamorphic character,  
these terranes are commonly affected by subsequent tectonothermal events. Hence,  
their isotope systematics may be severely disturbed as a result of bulk chemical  
change or local isotopic homogenization. This leads to equivocal age and  
source information for different components within these terranes (see for  
example, [1-3]). In this paper we present Sr and Nd isotopic data for early  
Archean gneisses from the North Atlantic Craton in west Greenland and northern  
Labrador which have been affected by younger metamorphic events.

#### Regional Geological Setting.

(1) West Greenland. The early Archean Amitsoq gneisses of southern West  
Greenland were first identified around the mouth of Ameralik Fjord, ca. 15  
km south of Nuuk (Godthaab). In this area, both field and isotopic data document  
the existence of an ancient high-grade gneiss complex [4-6]. It is important  
to note that late Archean tectonothermal events (3100 to 2600 Ma) in this  
area were characterized by amphibolite facies rather than granulite facies  
metamorphic conditions, and that little migmatization occurred during this  
time interval. To the south and east, late Archean metamorphic grade reached  
granulite facies at 2900 - 2800 Ma, and mid-Archean tonalitic gneisses (correlated  
with 3050-2900 Ma Nuk gneisses in Godthaabsfjord) as well as later Archean  
granitoid gneisses, are volumetrically important. However, field studies  
suggest that an early component (Amitsoq gneiss) is present within these  
polyphase gneisses [7]. Relevant aspects of the regional geology are discussed  
in detail by McGregor et al., [7] and Nutman et al., [8]. Isotopic data for  
the gneisses are discussed in the context of three regional geologic field  
divisions:

(i) Amitsoq gneisses from type area (northwestern Buksefjorden and outer  
Ameralik). In this area there is evidence of ca. 3600 Ma granulite facies  
metamorphism [9].

ii) Amitsoq gneisses (from Nordafar) which are continuous with those in the  
type area but are strongly affected by late Archean granitoid injection and  
variable metasomatic alteration. The late granites probably formed as a result  
of granulite facies metamorphism at depth.

iii) Gneisses further to the south and east (at Kangimut sangmissoq, Tinissaq  
and Ikerasakisup akornga) which preserve field characteristics of Amitsoq  
gneisses but were metamorphosed under granulite facies conditions at ca. 2900  
to 2800 Ma and subsequently experienced patchy retrogression under amphibolite  
facies conditions. These units are not structurally continuous with the type  
Amitsoq gneisses to the northwest.

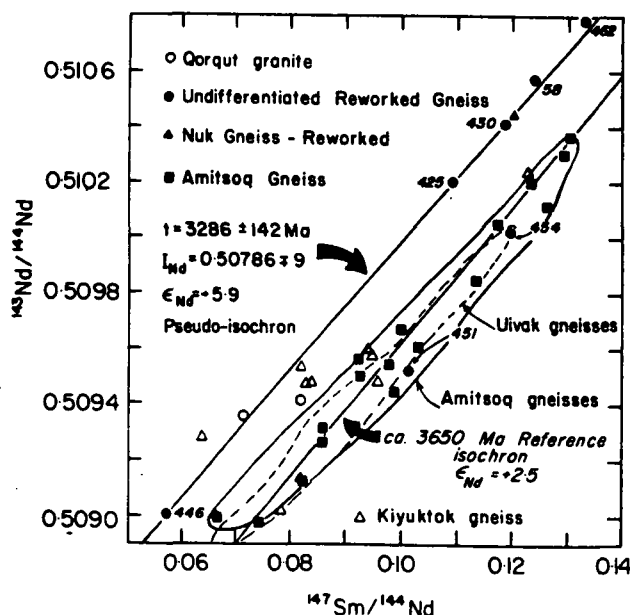
(2) Northern Labrador

The Uivak 1 gneisses and the interleaved Nulliak (supracrustal) assemblage in northern Labrador are of similar age and character to rocks described above from west Greenland [10-13]. Large areas of northern Labrador show variable effects of late Archean (ca. 2800 to 2900 Ma) granulite facies metamorphism. Early Archean relationships are best preserved on Big Island, Cape Uivak and the area immediately to the west and southwest, where late Archean metamorphic grade did not exceed amphibolite facies conditions. This is shown by Sr and U-Pb isotopic data presented in [14 & 15]. A striking feature of the early Archean Uivak 1 gneisses affected by the late Archean granulite facies event is the obliteration of early Archean fabrics by garnet and orthopyroxene porphyroblasts. This results in the development of a characteristic "blebby texture" [11] in the quartzofeldspathic gneisses. Development of this texture is associated with pervasive migmatization by granitic material. The resulting nebulitic assemblage constitutes the Kiyuktok gneisses [11]. Rocks similar to the Kiyuktok gneisses (albeit, generally strongly deformed) were recognized in west Greenland in 1984 [7]. The Kiyuktok gneisses, together with the Amitsoq gneisses discussed above, are interpreted to represent different evolutionary stages (and perhaps crustal levels) in the chemical and metamorphic differentiation of the gneiss complex in the North Atlantic Craton ca. 2800 to 2900 Ma ago.

Isotopic Data Nd and Sr isotopic data are presented in Figures 1 to 5. The following data presentation for each area is arranged in order of increasing severity of late Archean "reworking".

(1) Type Amitsoq gneisses. Sr isotopic data presented by Moorbath et al., [5] for mixed populations of Amitsoq gneisses yielded ages ranging between 3670 and 3612 Ma (recalculated using  $1.42 \times 10^{-11} \text{ a}^{-1}$  as the  $^{87}\text{Rb}$  decay constant). Initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios ( $I_{\text{Sr}}$ ) for these populations ranged between 0.7001 and 0.7015. Nd isotopic data for samples from the same area are shown in Figure 1. The data show a significant degree of scatter about the reference 3650 Ma isochron (calculated assuming that the  $I_{\text{Nd}}$  had a positive  $\epsilon_{\text{Nd}}$ ). The

Figure 1.



range in  $\epsilon_{\text{Nd}}(0)$  for the samples (ca. -28.5 to -56.4) reflects extreme fractio-

nation in  $^{147}\text{Sm}/^{144}\text{Nd}$  ratios and demonstrates their primitive character.  $T_{\text{CHUR}}^{\text{Nd}}$  model ages range from ca. 3300 to 3680 Ma. Similar Sr and Nd isotopic variations are observed in the best preserved Uivak I gneisses [14,16-19].

(2) Uivak gneisses. Nd isotopic data for the Uivak I gneisses exhibit a range of  $^{147}\text{Sm}/^{144}\text{Nd}$  values between 0.0612 and 0.1197, corresponding to  $\epsilon_{\text{Nd}}(0)$  of -63.1 to -35.4.  $T_{\text{CHUR}}^{\text{Nd}}$  model ages range from ca. 3300 to 3620 Ma. When regressed together with data for the early Archean Nulliak assemblage the total population yields an isochron with a slope equivalent to an age of  $3665 \pm 104$  Ma and an  $I_{\text{Nd}}$  of  $\epsilon_{\text{Nd}} +2.5/-+1$  [14 & 19]. U-Pb ion probe results for Uivak I zircon cores yield Concordia intercept and  $^{207}\text{Pb}/^{206}\text{Pb}$  ages ranging from ca. 3600 to 3900 Ma [2].

(3) Nordafar. Sr isotopic data for a varied suite of 8 samples of Amitsoq gneiss from this area yield a poorly correlated isochron (Fig. 2) equivalent to an age of  $3001 \pm 193/-153$  Ma with an  $I_{\text{Sr}}$  of  $0.7021 \pm 0.0020/+0.0017$  (regressed using

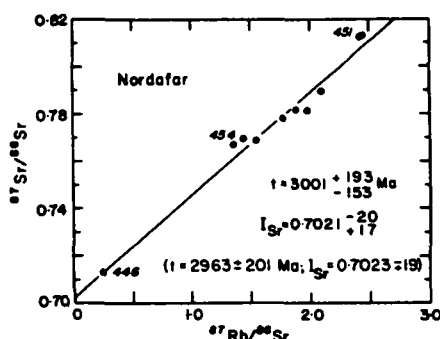


Figure 2

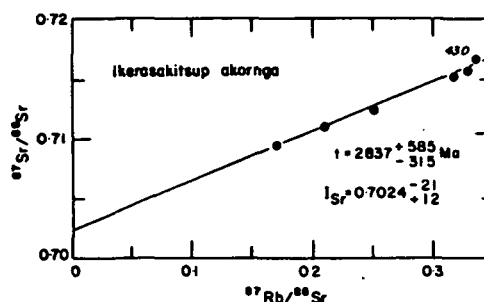


Figure 3

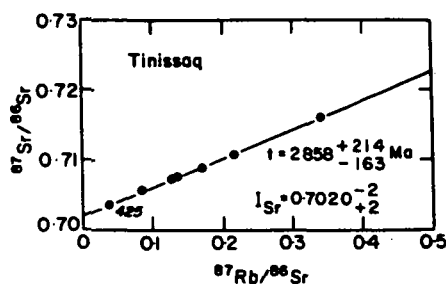


Figure 4

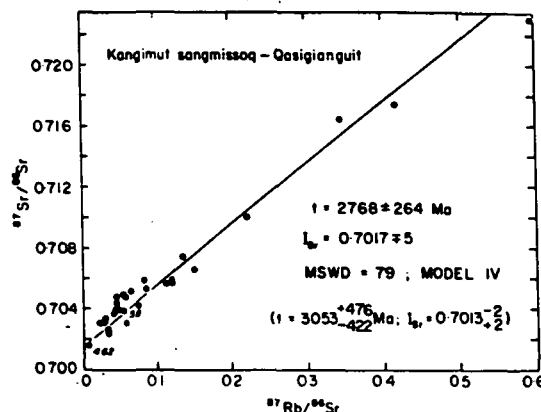


Figure 5

the method of Cameron *et al.*, [17] and assuming partial isotopic homogenization at 1800 Ma). Nd isotopic data for three Nordafar gneisses (Fig. 1) lie within the scatter for the type Amitsoq gneisses. These samples yield  $T_{\text{UR}}^{\text{Sr}}$  model ages between ca. 3400 and 3200 Ma.

(4) Kiyuktok gneisses. Sr and Nd isotopic data for these rocks are discussed in [11, 14, 19-21]. The nebulitic reworked components of the Kiyuktok gneisses comprise varying proportions of old and new components. They have high  $I_{\text{Sr}}$ 's (ca. 0.7055 to 0.7081) and relatively unradiogenic Pb isotopic compositions which reflect involvement of pre-existing crust in their formation. Nd isotopic data for the Kiyuktok gneisses (Fig. 1) plot either within the Uivak I -



Amitsoq gneiss field or above this field, with more enriched radiogenic  $^{143}\text{Nd}$  compositions.

(5) Ikerasakitsup akornga. Sr isotopic data for felsic gneisses from this area are shown in Figure 3. They are moderately well correlated and define an isochron with slope equivalent to an age  $2837 \pm 585 / -315$  Ma and an  $I_{\text{Sr}}$  of  $0.7024 \pm 21 / +12$ . The large uncertainty in age results from limited dispersion in  $^{87}\text{Rb}/^{86}\text{Sr}$  within the suite. Nd isotopic data for specimen (430), the gneiss from this area which gives the oldest  $\text{TUR}^{\text{Sr}}$  model age (3284 Ma), is plotted in Figure 1. The  $\text{TCHUR}^{\text{Nd}}$  model age of this gneiss is 2755 Ma.

(6) Tinissaq. Gneisses from Tinissaq show greater dispersion in their  $^{87}\text{Rb}/^{86}\text{Sr}$  ratios than those from Ikerasakitsup akornga and define an isochron with slope equivalent to an age of  $2858 \pm 214 / -163$  Ma and an  $I_{\text{Sr}}$  of  $0.7020 \pm 2 / +2$  (Fig. 4). When Rb-Sr isotopic data for the Tinissaq and Ikerasakitsup akornga populations are regressed as a regional population using the McIntyre et al., [22] method they define a Model 2 isochron equivalent to an age of  $2906 \pm 136$  Ma with an  $I_{\text{Sr}}$  of  $0.7020 \pm 3$  (MSWD = 10). Using the Cameron et al., [17] method the age is  $2903 \pm 115 / -103$  Ma and the  $I_{\text{Sr}}$  is  $0.7020 \pm 2$ . Nd isotopic data for a single specimen of felsic gneiss from Tinissaq (425) are shown in Figure 1. This specimen has a slightly more fractionated REE pattern ( $\epsilon_{\text{Nd}}(0) = -31.9$ ) than the specimen from Ikerasakitsup akornga and yields a  $\text{TCHUR}^{\text{Nd}}$  model age of 2821 Ma.

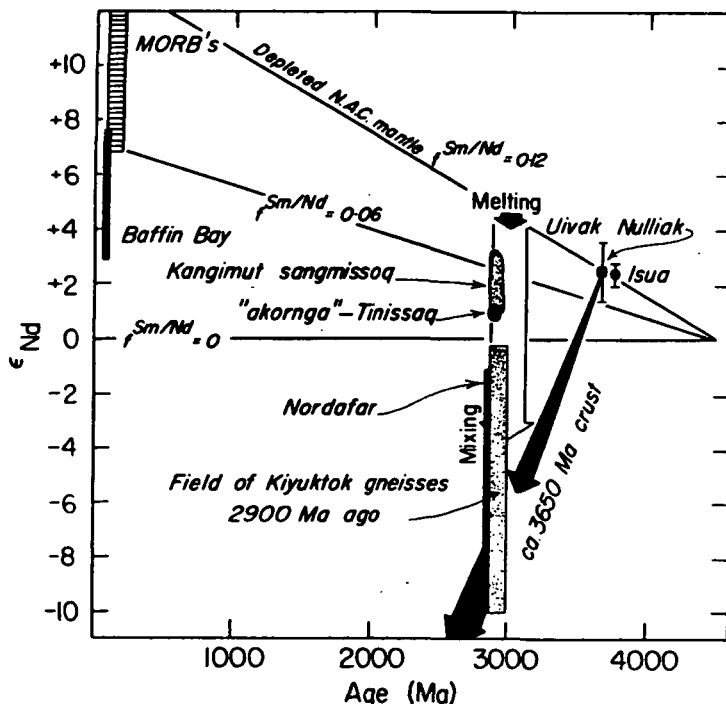
(7) Kangimut sangmissoq. Sr isotopic data for felsic gneisses from this locality (Fig. 5) are poorly correlated and define a McIntyre et al., [22] Model 4 isochron equivalent to an age of  $2768 \pm 264$  Ma with an  $I_{\text{Sr}}$  of  $0.7017 \pm 5$  (MSWD=79). The Cameron et al., [17] treatment for the same data is also shown in Figure 5. The large uncertainty in the age reflects the influence of the large population with  $^{87}\text{Rb}/^{86}\text{Sr}$  ratios less than 0.1. This depletion in Rb relative to Sr is a characteristic feature of gneisses from this locality. Nd isotopic data for two felsic gneisses are shown in Figure 1. They are less fractionated than the gneisses from the other localities and have  $\epsilon_{\text{Nd}}(0)$  values of -24.6 and -20.5 respectively.  $\text{TCHUR}^{\text{Nd}}$  model ages for these samples (viz., 2625 and 2508 Ma respectively) are significantly lower than model ages displayed by the other felsic gneisses. Also presented in Figure 1 are Sm-Nd isotopic data for a ca. 2900 to 3000 Ma Nuk gneiss from Kangimut sangmissoq, which has an  $\text{TCHUR}^{\text{Nd}}$  model age of 2773 Ma.

Discussion The different groups of felsic gneisses described above are considered to represent different stages in evolution of late Archean crust in the North Atlantic Craton. Sr and Nd isotopic data for most of the gneisses yield equivocal information regarding the crustal prehistory of the gneiss complex. This is particularly true when different groups are studied in isolation. Only the type Amitsoq and Uivak 1 gneisses preserve unequivocal Sr and Nd isotopic evidence of the antiquity of their protoliths. The Kiyuktok gneisses and some of the Nordafar gneisses preserve information about their crustal history in their Sm-Nd isotope systematics (see Fig. 1). However, the Rb-Sr isotopic evolution of the Nordafar gneisses differs from that of the Kiyuktok gneisses and yields no information concerning a possible crustal pre-history (cf. data for the Kiyuktok gneisses, [11 & 21]). This contrasting pattern is interpreted to reflect either variation in metamorphic grade of the early Archean protoliths of these rocks or variable enrichment in Rb during the ca. 2900 Ma metamorphic events (see Nutman et al., [8]). Gneisses at Ikerasakitsup akornga and Tinissaq have similar  $I_{\text{Sr}}$ 's to those at Nordafar (cf. Figs 2 to 4). However, unlike the Nordafar gneisses, their Nd isotope

systematics show no evidence that they contain an older crustal component. Most of the Kangimut sangmissoq gneisses are significantly more depleted in Rb relative to Sr than felsic gneisses from the other areas and are characterized by less highly fractionated REE patterns. Nd isotopic data for these gneisses also show no evidence of an older crustal component.

When combined, the Nd isotopic data for Ikerasakitsup akornga, Tinissaq and Kangimut sangmissoq define a remarkably well correlated array (Fig. 1) with a slope equivalent to an age of ca. 3300 Ma and an extremely depleted  $\epsilon_{Nd}$  (+5.9). On face value this might be interpreted as having "real age significance". However, one of the samples from Kangimut sangmissoq which plots on this line is a ca. 3000 Ma Nuk gneiss also affected by the granulite facies event. This array is therefore interpreted as a pseudoisochron; probably a mixing line without any geochronological significance. The Sm-Nd isotopic systematics of samples which fall on this array, together with the Nordafar and Kiyuktok gneisses, are interpreted to have developed during the ca. 2800 to 2900 Ma tectonothermal event. The data appear to reflect mixing between isotopically evolved Uivak and Amitsoq crust ( $\epsilon_{Nd}$  -8 to -12 at ca. 2900 Ma) and a juvenile-like component, possibly derived from a depleted mantle source with  $\epsilon_{Nd}$  of +4 to +6 at ca. 2900 Ma. The nature of this juvenile component or the mechanism by which the interaction occurs has not yet been established. The model is depicted graphically in Figure 6. Nd isotopic data for Tertiary

Figure 6



basalts flanking, and formed during the opening of Davis Strait, when Labrador was separated from west Greenland clearly have been derived from depleted mantle source regions. The Baffin Bay data, combined with the postulated evolutionary vector for the mantle source region of the early Archean suites, demonstrates that the mantle beneath the North Atlantic Craton would have had the appropriate depleted character at ca. 2900 Ma required by the postulated mixing process. A similar model was suggested by Collerson and McCulloch [14] for the Kiyuktok gneiss and is strengthened by the data presented for the west Greenland gneisses.

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VARYING ROCK RESPONSES AS AN INDICATOR OF CHANGES IN  $\text{CO}_2$  -  $\text{H}_2\text{O}$  FLUID COMPOSITION; C.R.L. Friend, Dept. of Geology & Physical Sciences, Oxford Polytechnic, Headington, Oxon. OX3 0BP. U.K.

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The formation of the late Archaean charnockite zone of southern India has been ascribed to dehydration recrystallisation due to an influx of  $\text{CO}_2$  (1,2). PT conditions for the metamorphism have been calculated at about  $750^\circ\text{C}$  and 7.5 Kbar. The composition of the volatile species presently contained in fluid inclusions in the rocks changes across the transition zone. They are  $\text{CO}_2$  dominated in the granulite facies and  $\text{H}_2\text{O}$ -rich in amphibolite facies rocks. Additionally they demonstrate a decrease in pressure northwards away from the granulite facies (3). At the time of charnockite formation it has been estimated that activity of water was less than 0.35 (3). The charnockite is superimposed across an anatectic granite, the Closepet granite, but in places sheets of granite cut the charnockite (4). This led to the hypothesis that the two events were contemporaneous and that anatexis had occurred as a result of the increase in water activity in front of the influx of  $\text{CO}_2$  (5).

A study of the transitional zone was carried out at Kabbaldurga (Fig. 1) and it was recognised that the paths taken by the fluids could

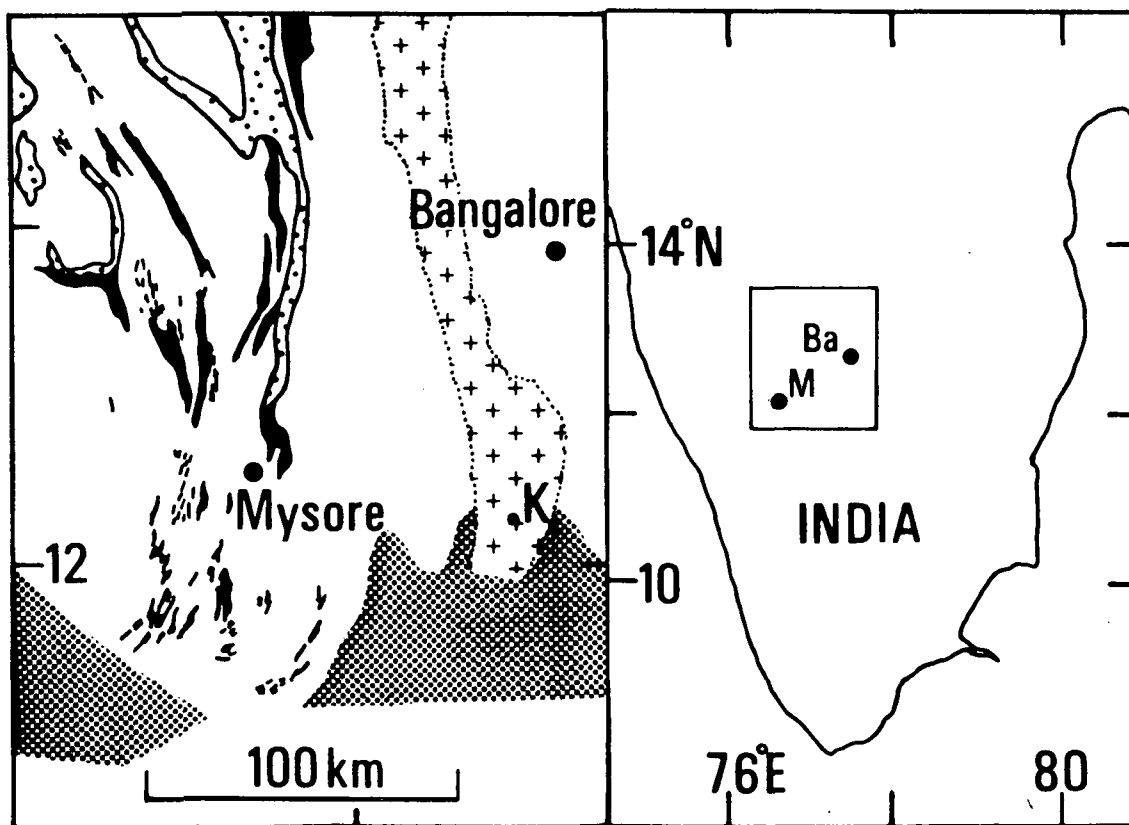


Fig. 1. Location of Kabbaldurga (K) and the charnockite zone (stippled). White = gneiss; black = Sargur supracrustal rocks; paired dots = Dharwar Super group.

be identified (6). In the charnockite terrain to the south, fluid migration appears to have been pervasive (cf. 7), the rocks having completely inverted to granulite facies assemblages (3), though some areas have been subjected to Proterozoic retrogression. However, at the transition zone it is clear that  $\text{CO}_2$  migration was, at least initially, channelled (cf 7). The channels are picked out as brownish hypersthene-bearing veins superimposed over the structure of grey amphibolite facies gneisses and pinkish granites (2,4,5). This channelled migration was controlled either by the fabric of the rocks, foliation surfaces and lithological layering, or by structural features. Development along shear zones is common and a rectilinear network of veins, often oblique to the fabric of the rocks suggests that active stress patterns were controlling fluid movements along microfractures.

It was reasoned that since there is evidence of the movement of  $\text{CO}_2$ , as a result of dehydration effects upon the rocks, it may be possible to find a sequence of change laterally along a pathway (6). It is evident that the charnockite veins die out laterally (2,5) and by looking at the detailed structure of the veins a complete progression was recorded (6). Briefly this sequence passes from completely recrystallized charnockite into incipient charnockite, where there is occasionally, relics of the original structure, and then into a pathway along which only minor modification of the texture has taken place before passing into a reddened vein in the country rock. In this latter portion of the pathway it was concluded that the release of water by dehydration reactions had so modified the composition of the invading fluid that it was no longer capable of causing hydrates to breakdown, the reddening simply reflecting the passage of fluid.

The ingress of  $\text{CO}_2$  is considered to have taken place into what initially was a closed<sup>2</sup> system so that water flushed out from lower levels accumulated in front of the  $\text{CO}_2$  advance and locally may have become ponded (8) causing local partial melting to occur in the amphibolite facies rocks. Subsequently channelled  $\text{CO}_2$  created the network of charnockitic veins superimposed over the country rock fabric and structure (fig 2), which includes local zones of anatexis. Lateral change along the veins is explained by inhomogeneity in the fluid composition in the rock which locally may have had the ability to buffer the incoming fluids whilst elsewhere the system was flooded (cf 7).

At Kabbaldurga the passage of fluids may be attributed to channelled flow. However, important information may be gained which may help in understanding the flow regime in the totally inverted granulite facies rocks to the south where they appear to have suffered pervasive flow. In certain parts of Kabbaldurga quarry there are areas of totally inverted charnockite around which are arranged network arrays of charnockite veins (fig 2). In these areas the decrease in intensity of charnockite formation along the length of the pathway is evident over several metres. Between the veins cells of amphibolite facies rocks remain which decrease in size towards the area of charnockite (fig 2). In the areas of solid charnockite it would appear that pervasive flow of  $\text{CO}_2$  has occurred. However, the evidence from the networks would suggest that two separate processes are going on.  $\text{CO}_2$  has free access along the channels which are structurally held open, and the mafic phases are dehydrated to

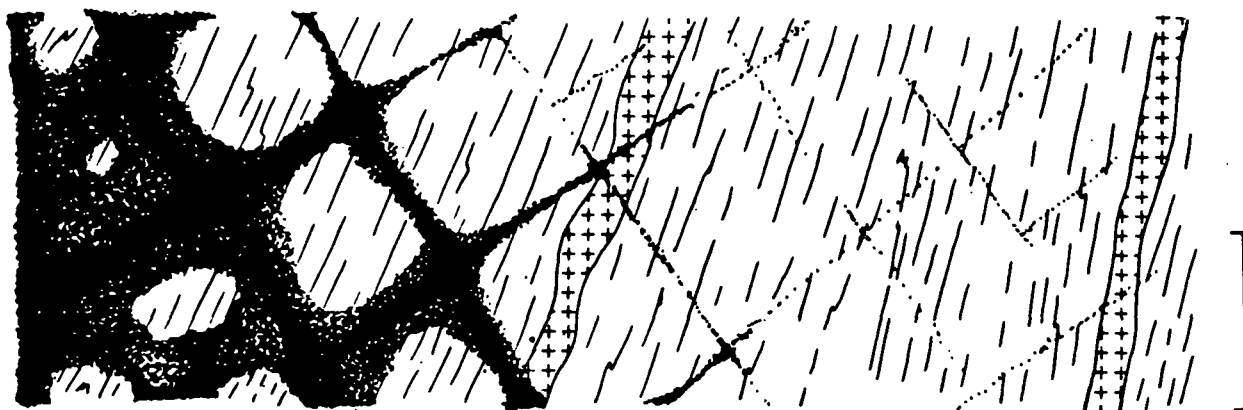


Fig. 2. Schematic plan of a segment of a charnockite area and surrounding network of veins (black), showing cells of amphibolite facies countryrock remaining (dashes = gneiss; crosses = granite). Scale bar = 1m.

orthopyroxene + a new biotite. The dehydration of the cells would appear to be a process which is controlled on a local scale by the rate of breakdown of hydrates along the walls of the main  $\text{CO}_2$  channel. Clearly  $\text{H}_2\text{O}$  is low in the channel, thus a gradient exists between the channel and the cell, where  $\text{H}_2\text{O}$  is high. It is thus possible that fluid flow in the charnockites to the south was also channelled and not necessarily pervasive.

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DEVELOPMENT OF ARCHEAN CRUST IN THE WIND RIVER MOUNTAINS,  
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W9901063

The Wind River Mountains are a NW-SE trending range composed almost entirely of high-grade Archean gneisses and granites which were thrust to the west over Phanerozoic sediments during the Laramide orogeny. Late Archean granites make up over 50% of the exposed crust and dominate the southern half of the range, while older orthogneisses and migmatites form most of the northern half of the range (Fig. 1). Locally these gneisses contain enclaves of supracrustal rocks, which appear to be the oldest preserved rocks in the range. Detailed work in the Medina Mountain area of the central Wind river Mountains and reconnaissance work throughout much of the northern part of the range has allowed us to define the sequence of events, described briefly below, which marked crustal development in this area.

I. Sequence of events in the Medina Mountain area

The oldest rocks present in the Medina Mountain area consist of a paragneiss-rich migmatite and a supracrustal succession (Fig. 2). At least two discrete sedimentation events are preserved. The older sequence consists of mafic rocks (metavolcanics?), calc-silicates, iron formation and rare pelites and occurs as melanosomes in a migmatitic gneiss. Also found within the migmatitic gneiss are enclaves of metamorphosed peridotites, pyroxenites,

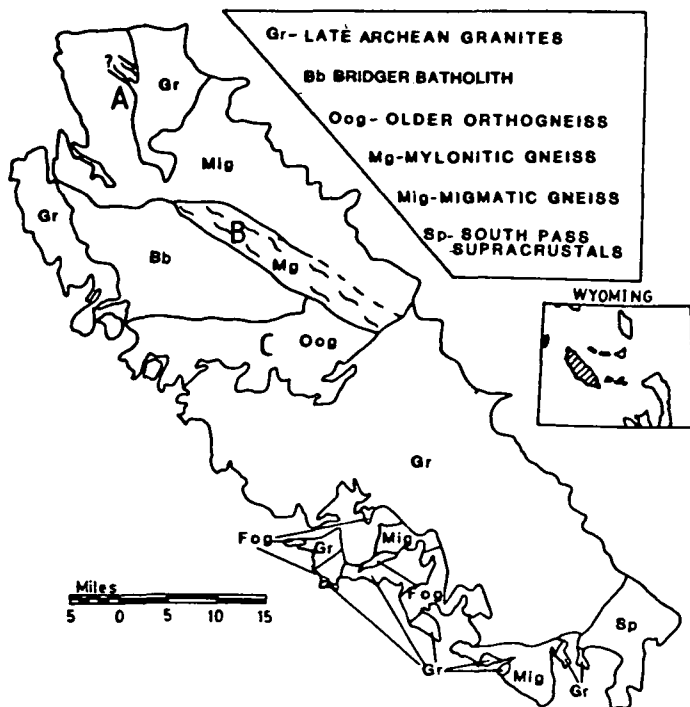


Fig. 1. Regional Geology of the Wind River Range, Wyoming.

A = Downs Mountain Area;  
B = N. Fork Bull Lake Creek Area; C = Medina Mountain Area.



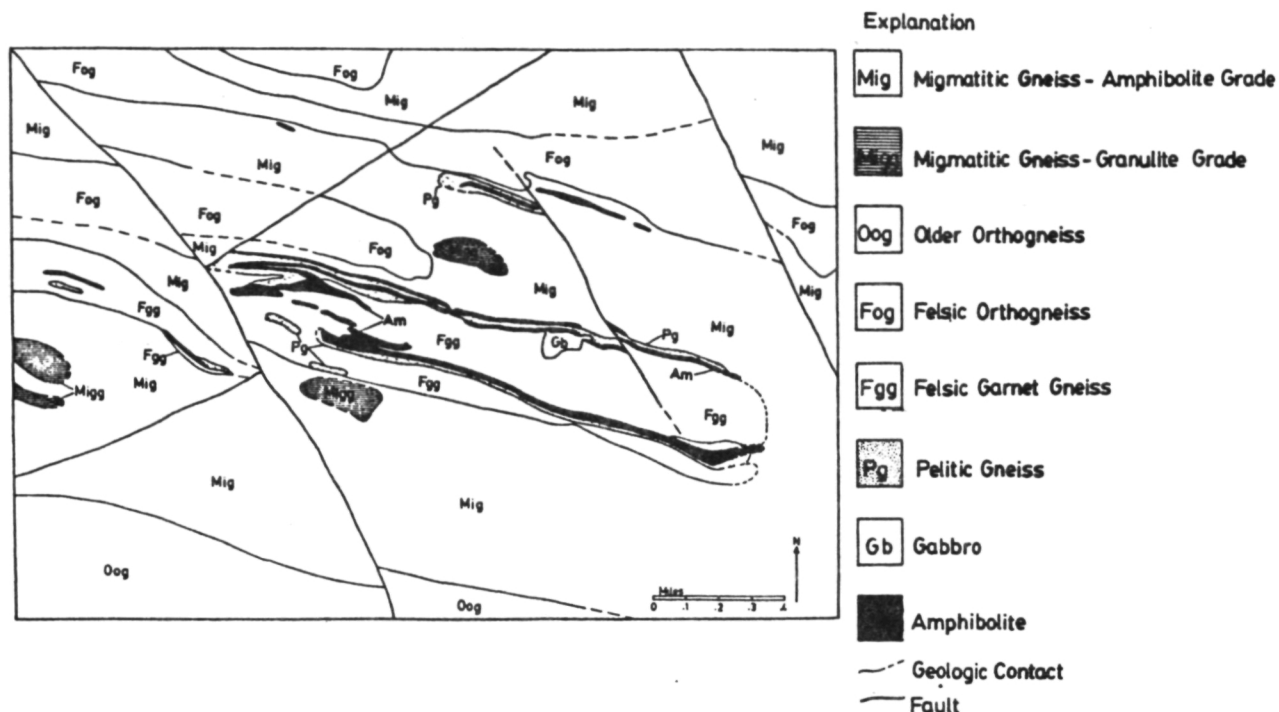


Fig. 2. Geology of the Medina Mountain Area.

gabbros and leucogabbros. These rocks seem to have suffered the same complex metamorphic and intrusive history as the older supracrustal rocks but the age relations between them and the supracrustal rocks are not known.

This sequence of rocks was injected and migmatized by an early set of granitoid dikes, isoclinally folded and subjected to regional metamorphism that reached granulite facies in this area. Following these events, thin, porphyritic mafic dikes and volumetrically minor amounts of tonalite were intruded. Because these dikes and tonalite sheets cross-cut the migmatitic gneiss and do not cross-cut the younger supracrustal sequence, they form an important marker in the geologic evolution of the area.

The younger supracrustal sequence consists of banded amphibolites (metavolcanic?), calc-silicates, semipelitic and pelitic gneisses. The succession defines a large-scale synformal structure that is locally migmatized by sheets and irregular layers of felsic garnet gneiss.

Portions of the felsic garnet gneiss are interpreted to be a partial melt of the metasediments and formed during the last regional metamorphism of the Medina Mountain area.

Late Archean granitoid plutons intrude and locally crosscut the entire Medina Mountain sequence. These late plutons range from granodiorite to granite, are weakly deformed, and retain igneous textures. The Bridger batholith to the north is strongly to weakly foliated and has a metamorphic mineralogy, but locally retains igneous textures. The batholith crosscuts older orthogneisses and migmatitic gneisses.

## II. Archean Lithologies Elsewhere in the Wind River Range

Blocks and pods of supracrustal rocks are found in orthogneisses in many areas of the northern and central Wind Rivers, although nowhere are they as coherent as near Medina Mountain. Lithologically, these rocks are very similar to the Medina Mountain supracrustals, consisting of fine grained, banded mafic gneisses thought to be of metavolcanic origin, pelitic and semi-pelitic metasediments, quartzite, and iron-formation. As in the Medina Mountain area, metaperiodotites and metagabbros are intimately associated with the supracrustals in many places in the northern part of the range. Many of these supracrustal enclaves are found within the Mt. Helen Structural Belt (mylonitic gneiss, Fig.1) which is a major orogenic feature associated with the latest regional metamorphism and deformation. Tonalitic gneiss, though present in the northern part of the range and to the west of Medina Mountain does not make up the major portion of the older rocks, as appears to be the case in many other Archean terranes.

## III. Metamorphism

At least two Archean high-grade regional metamorphic events have affected the Wind River Mountains. The last regional metamorphism attained amphibolite grade over most of the range. Metamorphic conditions for this event were around 700°C and 4.5 kilobars in the Downs Mountain area in the northern part of the range (1) and in the N. Fork Bull Lake Creek area (2) (Fig.1). In the Medina Mountain area the younger supracrustal rocks are locally upgraded to granulite facies.

In the North Fork Bull Lake Creek area, the supracrustal inclusions

commonly have cores with granulite mineralogies. Field relations indicate that this granulite metamorphism preceded emplacement of many of the orthogneisses and hence is older than the second regional metamorphism. Conditions for this metamorphism are difficult to determine because ion-exchange geothermometers and geobarometers were reset during the second high-grade metamorphic event. The widespread occurrence of the assemblage garnet-orthopyroxene-cordierite, however, allows one to establish that the pressure was 6kb or less and that the maximum temperature was below 780°C (Fig.3).

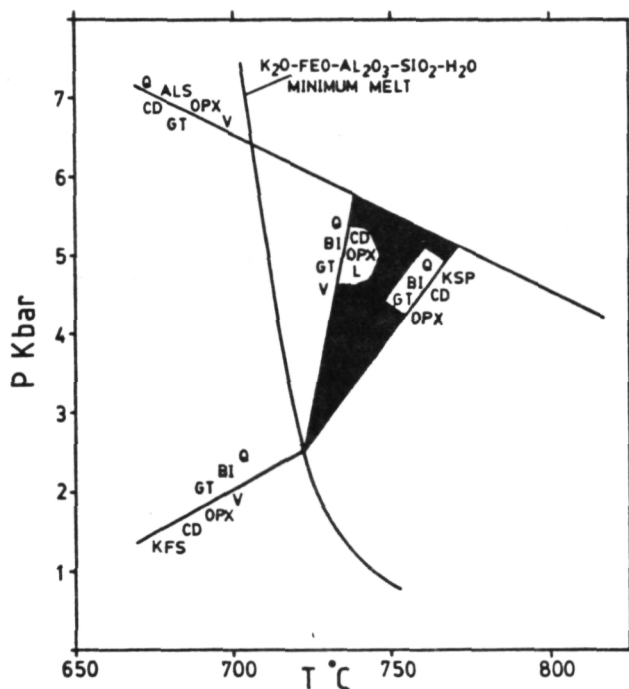


Fig. 3. P-T diagram showing stability field for garnet-cordierite-orthopyroxene. Shaded area indicates probable equilibrium conditions for first metamorphic event. From Grant, (6).

#### IV. Isotope geochemistry and geochronology

Of the sequence of events outlined above, absolute ages are known only for the Late Archean intrusions. Stuckless et al. (3) have obtained U-Pb and Rb-Sr dates on two granitoid lithologies of  $2.63 \pm 0.02\text{Ga}$  and  $2.50 \pm 0.04\text{Ga}$ . The Bridger batholith, which outcrops immediately to the north of the Europe canyon area, has been dated at  $2.67 \pm 0.04\text{Ga}$  (C.

Frost, unpublished Rb-Sr data). Since this pluton is interpreted as having been intruded during the waning stages of metamorphism and deformation, its age provides an upper limit on the time of latest regional metamorphism.

Nd crustal residence ages, which provide an estimate of the average period of time the protoliths of a particular unit have resided in the crust (4), have been calculated for samples of the Bridger batholith. All of the samples yield crustal residence ages of around 2.9 Ga, only around 200 Ma in excess of intrusive ages. The difference between crustal residence and intrusive ages for Bridger batholith gneisses is small compared to other late Archean granitoids (5) and indicates either that the rocks are derived mainly from mantle materials with a small proportion of significantly older crustal component, or that the intrusives are derived mainly from crustal materials which are on average only slightly older than the intrusives themselves. Field and textural evidence indicates that significant portions of the supracrustal sequence had begun to melt under conditions of peak metamorphism; however, it is uncertain how much of this melt has been incorporated into the Bridger batholith.

#### V. Summary

The essential features of Archean crustal development in the Wind River Mountains are as follows:

1. Supracrustal rocks and paragneiss-rich migmatites are the oldest materials preserved in the range.
2. Unlike many other Archean terranes, tonalitic rocks are volumetrically minor.
3. The Archean crust of the Wind River Mountains was subject to multiple deformation and metamorphism prior to 2.7 Ga.
4. Late Archean granitoid intrusions comprise a large proportion of the range. They have been derived in part from crustal melts produced during the last Archean metamorphism.

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# ORIGIN AND EVOLUTION OF THE AMAZONIAN CRATON

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The Amazonian craton appears to have been formed and modified by processes much like those of the better-known Precambrian cratons, but the major events did not always follow conventional sequences nor did they occur synchronously with those of the other cratons. Much of the craton's "Archean style" continental crust formation, recorded in granite-greenstone and high-grade terranes, occurred in the Early Proterozoic: a period of relative quiescence in many other Precambrian regions. Some of the Archean rocks originated in continental settings. The common Archean to Proterozoic transition in geological style did not occur here, but an analogous change from abundant marine volcanism to dominantly continental sedimentary and eruptive styles occurred later, during the ~2 Ga Trans-Amazonian orogenic cycle.

Amazonian geology is summarized in Fig. 1 and Table 1 (see also recent reviews: 1-3a). The Amazon basin divides the craton into the Guiana (northern) and Guapore Shields, with Precambrian geology easily matched across the basin. Archean rocks in the northern (Imataca) and southeastern (SE Para, Brazil) extremities of the craton are separated along the northern and northeastern craton margins by an Early Proterozoic granite-greenstone terrane. Most of the remaining area is an immense anorogenic felsic igneous terrane, with felsic rocks belonging to or correlated with the Uatuma (1.7-1.9 Ga) and Parguaza (~1.5 Ga) cycles. The Early Proterozoic Central Guiana Granulite Belt (CGGB), divides both the adjacent granite-greenstone and Middle Proterozoic terranes in the Guiana Shield.

ARCHEAN TERRANES: The Imataca Complex includes medium to high-grade quartz-felspathic paragneisses and iron formations accompanied by acid, intermediate, and mafic granulites and orthogneisses, dolomitic marbles, manganese-rich metasediments, and anorthosites (4,5). Intense Trans-Amazonian deformation, metamorphism, and isotopic resetting obscure its Archean history (6). The Imataca Province also includes small areas with undated greenstone-belt lithologies. The province is in (thrust?) fault contact with the adjacent Early Proterozoic granite-greenstone terrane (7). It may be correlated with the Kenema-Man domain of west Africa (8), which also has Archean high grade rocks, iron formations, and fault contact with the adjacent Early Proterozoic terrane. They may once have been contiguous, and their faults may belong to the same system, according to paleomagnetic evidence (9).

Both low and high-grade Archean rocks are present in SE Para (~6°-10° S). Archean greenstone belts with pillow basalts and komatiites, amphibolite belts, and granitoid rocks and gneisses (10) form a basement to the low-grade Grao Para Group at Serra dos Carajas (Fig 1.). The Grao Para hosts the major Serra dos Carajas iron formation and was considered Proterozoic, but we recently obtained a rhyolite zircon age of 2.75 Ga for it. The group has an apparent minimum thickness of about 6 km and consists of bimodal, partially spilitized metavolcanic rocks overlain by 100-300 m of iron formations, overlain in turn by more basalts (10,11). Subalkaline basalts with flat REE patterns (10x chond) and basaltic andesites and shoshonites with LREE-enriched and flat HREE patterns predominate over rhyolites. The mafic rocks are unlike typical Archean basalts and basaltic andesites, but resemble those of Triassic rift rocks of eastern North America, consistent with their eruption through continental crust. They also resemble Proterozoic bimodal volcanics of the SW USA, which have been attributed to a rifted continental setting (12). Shales, tuffs, conglomerates, arkoses, quartz arenites, and iron, manganese, silica,

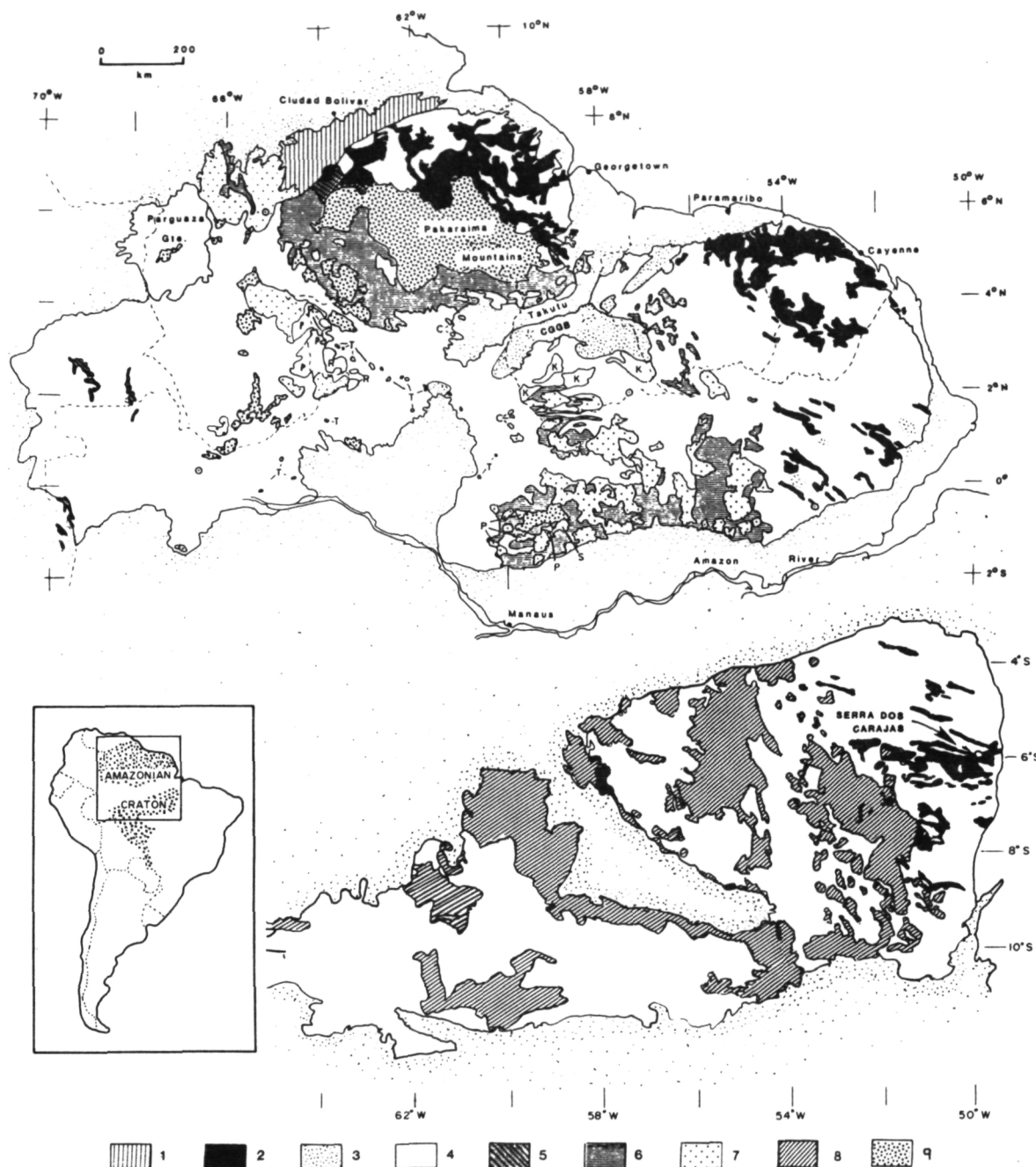


Figure 1. Outline geology of the Amazonian Craton [compiled from Anonymous, 1977; Bellizia et al, 1976; Gibbs and Barron, 1983; Metallogenic Map of South America, 1984; Schobbenhaus et al, 1981]. Key: 1- Imataca Complex; 2- greenstone belts; 3- high-grade terranes; 4- undifferentiated granites and gneisses; 5- Middle Proterozoic pre-Uatuma sedimentary rocks; Uatuma Supergroup (6-8): north of the Amazon; 6- volcanics; 7- granitoid rocks; South of the Amazon, 8- Uatuma granitoid, volcanic and various sedimentary rocks; 9- Roraima Group sedimentary rocks; Other features: C- Early Proterozoic Cauarane Gp.; K- Early Proterozoic Kwitaro Gp.; P- Mid. Proterozoic Parquazan granites; R- Early Proterozoic Parima Gp. supracrustals; S- Later Proterozoic Seringa Fm; T- Trans-Amazonian Tapuruquara Suite mafic intrusives. Small circles- alkaline complexes.

TABLE 1: Major Precambrian Events of the Amazonian Craton.

Age (Ga)	Basement Terranes			
	Imataca Province	Northern Granite -Greenstone Terranes	Central Guiana Granulite Belt	Southeast Para, Brazil
0	Events of the Continental stage, superimposed on all of the basement terranes			
	Rifting, mafic igneous activity, and sedimentation in Amazon and Takutu basins			
1	K-Ar cooling Ages (.9 - 1.3 Ga), faulting alkaline complexes (ages uncertain)			
	Parguazan granite intrusions (1.45 - 1.55 Ga)			
	Mafic intrusions (1.6 Ga)			
	Continental sedimentation (1.65 - 1.9 Ga) and Uatuma cycle felsic intrusion and volcanism (1.75 - 1.9 Ga)			
	Mafic dike and sill intrusions (1.8 Ga)			
2	Trans-Amazonian Orogeny: metamorphism, mafic and granitoid intrusives			
	Events older than this apply to specific basement terranes			
		volcanism, sedimentation and granitic intrusion (2.1 - 2.25 Ga)	sedimentation and volcanism  basement?	clastic sedimentation (age uncertain)  ~~~~~?~~~~~
	Metamorphism (2.7 Ga), Igneous activity and iron fm. deposition?			Iron formation, volcanism, (2.7 - 2.8 Ga)
3	~~~~~?~~~~~  Protolith of some Imataca complex rocks, (>3.4 Ga)			Gneisses and green- stone belts (ages uncertain)

and carbonate chemical sediments overlie the Grao Para Group in a pattern that is broadly concordant on a map scale, but may actually be unconformable. These sedimentary rocks might be Archean, or as young as Middle Proterozoic.

The boundary between the Archean crust of the Carajas region and the Early Proterozoic crust of French Guiana has not been adequately determined. Some suggest that it is located immediately north of Carajas, striking E-W (13). The similarity of map pattern of the (undated) belts of Amapa (0°- 2°N) and Carajas suggests that Amapa may be part of the same terrane, and may thus also be Archean. Gneisses and granulites that separate the Amapa greenstone and amphibolite belts have been considered by some to be Archean, though only tenuous isotopic evidence in support of this interpretation has been published (14).

Archean Amazonian iron deposits have features in common with both Algoma and Superior types. The dimensions and lateral persistence of both the Carajas and Imataca deposits are like those of Superior type; the association of the Carajas deposits with basalts is an Algoma-type feature.

**EARLY PROTEROZOIC GRANITE-GREENSTONE TERRANES:** All the autochthonous constituents of the northern Guiana Shield are thought to have emerged from the mantle during the Early Proterozoic. Greenstone belts are the oldest dated units; they have yielded 2.1-2.3 Ga U-Pb zircon and Sm-Nd ages (15-18). Gneisses and amphibolites in the same terranes have yielded similar and younger ages, and appear to be the intrusive associates and metamorphosed equivalents of the greenstone belt rocks (15,16,18-20a). Low initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios (<.703) are consistent with little involvement of older continental crust in the generation of the Trans-Amazonian granitoid and



metamorphic rocks of the northern craton. The greenstone belts share similar lithostratigraphy: lower dominantly low-K basalts overlain by interstratified mafic, intermediate, and felsic volcanics of both tholeiitic and calc-alkaline suites; overlain by and interstratified with volcanoclastic greywackes, pelites, and chemical sedimentary rocks (21-23). There are regional differences in the abundances and varieties of volcanic and sedimentary rocks: felsic volcanics are irregularly distributed, and magnesian basalts and possible komatiites are particularly common in central French Guiana (23) and Amapa (24). Sea-floor metamorphism as well as very low to medium grade regional and contact metamorphism have affected these belts, and folded, crenulated, and cataclased metamorphic minerals indicate a complex, multistage metamorphic history. Most northern Amazonian greenstone belts have a randomly-branching synclinal map pattern, but the eastern Amazonian greenstones and granitoid rocks belts have been elongated WNW by late Trans-Amazonian deformation.

Clastic sedimentary rocks of continental provenance are infolded with several of the Amazonian greenstone belts. Some form synclinal cores to the belts of northern French Guiana and Amapa. Stratigraphic relations between these rocks and the underlying greenstone belts are not well resolved. The abrupt appearance of rocks of continental provenance in belts that otherwise appear to have been formed in ensimatic settings may be accounted for by unconformity; by more gradual tectonically-controlled changes in the sedimentary source areas and depositional environments; or, possibly, some of the associated greenstone belts may actually be ensialic. These enigmatic continental sedimentary rocks and the underlying greenstone belts have much in common with the west African Tarkwaian and Birrimian, respectively.

**CENTRAL GUIANA GRANULITE BELT:** This extends from western Suriname into Roraima Territory, Brazil, and consists of medium- and high-grade metapelites, cross-bedded quartzites, calc-silicates, marbles, and ferruginous and manganiferous quartzites, as well as interstratified mafic metavolcanic rocks, and metagabbros and metadolerites (25-27). These metamorphic rocks have not yielded reliable ages older than Early Proterozoic (20,28,15). Their stratigraphy and relation to the rest of the craton are poorly known. The abundance of sedimentary rocks of continental provenance in the CGGB is not consistent with correlation of its supracrustal precursors with the Early Proterozoic greenstone belts of the northern terranes. The lack of evidence of Archean ages argues against their correlation with the Imataca or SE Para Archean. They might be another product of continental emergence during the Trans-Amazonian.

**TRANS-AMAZONIAN OROGENIC CYCLE:** Originally defined by the concentration of plutonic and metamorphic rock K-Ar and Rb-Sr model ages at about 2.0-2.1 Ga throughout the Amazonian craton (29), some have extended the term to include rocks of the 1.7-1.9 Ga Uatuma cycle. However, these younger rocks belong to a discordant, though only slightly younger stage of continental development (30). The cycle marks the assembly of diverse crustal fragments into a continent, their common deformation, and the first development of continental environments on much of the craton. Dikes and structures of the late Trans-Amazonian and succeeding Uatuma cycle are extensive, and demonstrate that the crust behaved in a continental fashion. Like the Kenoran orogeny in Canada, the Trans-Amazonian included multiple stages of intrusion, including tonalitic plutonic and hypabyssal intrusions, generation of two-mica "S"-type granitoid rocks, and even the possible intrusion of some kimberlites prior to the final stages of metamorphism and deformation (23). The cycle ended with WNW and ENE-striking cataclastic deformation of both plutonic and

metasupracrustal rocks prior to the deposition of the Uatuma Supergroup.

POST-OROGENIC EVOLUTION: Uatuma Supergroup and Parguaza granites and felsic volcanics, Roraima (1.85-1.65 Ga) and Gorotire Group arkoses, shales, quartz arenites and conglomerates, and 1.85 and 1.65 Ga mafic intrusives were emplaced in and on the upper crust of most of the Amazonian craton in the Middle Proterozoic. Only the northern and eastern margins and the CGGB lack evidence of this extensional and thermal modification, which affected both Archean and Early Proterozoic basement. The diffuse, 50-100 km wide Uatuma Sgp. boundary on the N and E cuts across older structures. Little is known about the ages of the pre-Uatuma basement in the vast central portions of the craton: few greenstone belts are exposed, and few ages in excess of 2 Ga have been determined. The Uatuma and Parguazan eruptions affected vast areas rather than linear belts, but there are indications that the ages progress from older (NE) to younger (SW), both in Venezuela (31) and in the southwest (32). Middle Proterozoic and younger faults and Paleozoic to Mesozoic dikes have reactivated Trans-Amazonian deformation zones, particularly the NE and ENE zone crossing the central Guiana Shield (33,34).

ACKNOWLEDGMENTS: Supported in part by the Guyana Geological Survey, the U.S. National Science Foundation (Grants EAR 7617026, 8207422, and 8410379), Utah International, DOCEGEO and ICOMI, Brazil, and the B.R.G.M., Direction Guyane. C.N. Barron, W. Hirata, J.O. Santos, X. Jorge Joao, A. Marot, J. Testard, and A. Filho have helped to develop our understanding of the regional geology; R. Kay and S. Mahlburg Kay provided valuable help in geochemical analyses; W. J. Olszewski, Jr., collaborated in zircon dating.

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CYCLIC GROWTH IN ATLANTIC REGION CONTINENTAL CRUST; A.M. Goodwin, Department of Geology, University of Toronto, Toronto, Canada M5S 1A1

The four continents of the Atlantic region -- Europe, North America with Greenland, South America, and Africa with Arabia and Madagascar -- contain large Precambrian platforms which, together with adjoining Phanerozoic mobile belts, give evidence of cyclic continental growth, involving regular ca. 400 Ma-long cycles.

Precambrian continental platforms comprise both exposed shields and buried basement. Recently compiled maps serve to provide the areal proportions by eon and era of exposed and buried rocks in the Precambrian platforms of the Atlantic region (Table 1). Because the basis of classification is radiometric dating, rocks assigned to an era include both newly formed rocks and reworked (metamorphosed) older crust. Thus areal proportions by era reflect accumulated orogenic history, the younger eras gaining at the expense of the older. In fact significant survival of older crust e.g. Archean (14%) and Early Proterozoic (22%), requires enduring cratonization during continental growth, attributable to deep sub-shield tectospheric roots (1).

The proportions by era (and eon) (A,B,C,D in Table 1) of exposed Precambrian crust only in the combined continents of the Atlantic region are roughly equal with A (33%) being the highest and B (21%) the lowest. Considered by continent, divisions C and D are significantly high in North America, B in South America, and A in Africa; A and B are unusually low respectively in North America and Africa. However, considering entire platforms (exposed & buried Precambrian crust) the youngest era (A) predominates as expressed in D:C:B:A = 1 : 1.6 : 1.3 : 3.3. Geologically this expresses 1) widespread Pan-African influence in Africa and South America, and 2) the presence of large Late Proterozoic-Phanerozoic-filled basins in Europe (Moscow Syncline) and Africa (Taoudeni and Congo).

Considering relative sizes by continent of Precambrian platforms and adjoining Phanerozoic mobile belts (Table 2), the European platform is the smallest and the African platform the largest (x3.7). Phanerozoic belts of Europe (Hercynides-Caledonides-Alpides) are the largest, and of Africa (Cape-Mauritanides-Atlas) the smallest. In all continents except Europe the Precambrian platform is substantially larger than the adjoining Phanerozoic mobile belts. The combined continental crust by continent is, in increasing order of size, South America, Europe, Africa, North America. Thus each continent is an aggregate of partly covered interior Precambrian platform of designated composition and peripheral Phanerozoic mobile belts.

Gastil (2) established that abundant global igneous and metamorphic dates, corresponding to periods of orogeny, are about 210 Ma in length, and alternate with like periods of mineral date scarcity (tectonic quiescence) for a mean 417 Ma-long cyclic distribution pattern extending back to 2600 Ma. This pattern corresponds to long cycles in Earth's orogenic history, the peaks in the number of radiometric ages corresponding to terminal events of the major crustal processes. Post-1960 dating, extending back to 3.8 Ga, supports the validity of Gastil's main peaks of mineral dates marking global orogenies and accelerated crustal growth. The main culminations occur approximately at 2.6, 1.8, 1.0 and 0.6 Ga, which respectively demarcate Archean eon (D), and Early-(C), Mid-(B), and Late-Proterozoic (A) eras; others are dated at 3.5, 3.0 and 2.2 Ga. In close accord, Cahen et al. (3) select the following dates as chronological milestones in the evolution of Africa, the continent with the largest Precambrian platform (Table 2), each

date marking the approximate age of comparatively widespread events: 3.5, 2.9, 2.5, 2.1, 1.75, 1.1 and 0.57 Ga.

Culminations of the same crustal processes are also reflected in the post-Archean paleomagnetic record by "hairpin" turns which mark sudden reversals in the sense of polar motion of continental plates (4). Worsley et al. (5) summarize a "non-random" crustal model to account for long-term tectonic cyclicity. Plate motion is attributed, accordingly, to a thermal instability mechanism (6) resulting from the repeated assembly of supercontinents (Pangea) that never completely disperse. A pattern of plate tectonic cycles, each cycle of about 400 Ma duration, is recognized back to 2000 Ma. The popular "random" plate motion model (7), however, advocates that Mesozoic Pangea represents assemblage of continental fragments dispersed from a still-earlier supercontinent centred on the Pacific Ocean, and now marked by the central Pacific residual geoid high. Le Pichon and Huchon (8) in turn, interpret evidence pertaining to the geoid and supercontinent in terms of a weak coupling of a separate steady-state lower mantle, which is responsible for the present geoid, to upper mantle convection leading to hemispheric continental configuration (Pangea) which ends when excessive heating of the upper mantle due to the insulating continental cap leads to continental dispersal, the complete cycle from one supercontinent to the next being in the order of 400 Ma. Thus whatever model is used, the evidence points to regular cyclicity in the evolution of continental crust. Specifically, taken together with the ongoing plate cycle (since 0.2 Ga), the data on Atlantic region crust provide for a regular cyclic pattern of about 400 Ma duration, a pattern involving 8 cycles back to 3.0 Ga.

The Atlantic region of the collective Europe-Americas-African plates has experienced repeated horizontal crustal oscillations. Including the modern Atlantic opening, at least 3 (to 1.0 Ga) and possibly 4 (to 1.4 Ga) coherent Wilson cycles have been tracked, each involving early divergence with supracrustal accumulation followed by convergence and orogeny over about 400 Ma. For the most part these particular cycles are readily interpreted in terms of modern plate tectonic processes involving ocean floor consumption with active and passive continental margins. However, whereas certain intercontinental Pan-African belts, e.g. Pharusides, do likewise carry Wilson cycle signature, others, e.g. Damara-Katanga, Ribeira, Paraguay, are apparently ensialic in origin and suggest a different tectonic origin. Mid-Proterozoic (B) crust (cycles 4,5) is characterized by widespread anorogenic magmatism, aborted rifts and aulacogens together with major mobile belts (Grenville, Rondonian), some apparently ensialic (Kibarides, Espinhaco). Paleomagnetic data suggests a single stable supercontinent (9). The nature of the operating plate tectonic processes is highly controversial and uncertain. Early Proterozoic (C) crust (cycles 6,7) features numerous, commonly asymmetric fold belts which appear, more often than not, to be superposed on an ensialic basement. Some belts, however, e.g. Coronation, closely resemble Phanerozoic equivalents. Still others, e.g. Birrimian, contain Archean-type greenstone belts. Most belts are severely deformed as a result of low-angle foreland transport. This tectonic mobility is frequently followed by intensive and repeated granitoid intrusion, commonly with ring-structures, generally high-level, often alkaline, and linked to lava extrusion, all conducive to cratonization. Finally Archean (D) crust (cycle 8+) contains the well known low-to-medium grade granitoid-greenstone belts and higher grade gneiss-migmatite terrains, commonly granulitic. Up to three generations of greenstone belts are known in some regions. Numerous accretion-differentiation episodes occurred locally in near-continuous

succession. Widespread tonalite plutonism led to rapid growth of stable cratons. In keeping with its antiquity and uniqueness the nature of the formative plate tectonic processes is largely unresolved.

In brief, Atlantic region continental crust evolved in successive stages under the influence of regular, ca. 400 Ma-long tectonic cycles. Data point to a variety of operative tectonic processes ranging from widespread ocean floor consumption (Wilson cycle) to entirely ensialic (Ampferer-style subduction or simple crustal attenuation-compression). Different processes may have operated concurrently in some or different belts. Resolving this remains the major challenge.

Table 1. Areal Proportions by Era of Exposed and Buried Precambrian Crust in Precambrian Platforms, Atlantic Region.

Precambrian Platform (10 <sup>3</sup> km <sup>2</sup> )	Precambrian Era and Eon (%)			
	Proterozoic Era			D. Archean Eon (+2.6 Ga)
	A. Late (0.6-1.0 Ga)	B. Mid- (1.0-1.8 Ga)	C. Early (1.8-2.6 Ga)	
I Exposed Crust Only in Platform				
Europe (1,595)	35	17	28	20
North America (5,969)	10	23	37	30
South America (5,366)	33	36	15	16
Africa (10,684)	54	8	18	20
Total Atlantic Region (23,614)	36	19	23	22
II Combined Crust (exposed + buried) in Platform				
Europe (7,572)	45	11	20	24
North America (19,470)	4	30	49	17
South America (12,969)	48	28	17	7
Africa (28,381)	75	6	7	12
Total Atlantic Region (68,392)	46	18	22	14

Table 2. Relative Sizes by Continent of 1) Precambrian platforms 2) adjoining Phanerozoic mobile belts, and 3) combined continental crust.

Continent	Precambrian Platform		Phanerozoic Mobile Belts		Combined Continental Crust	
	Size (10 <sup>3</sup> Km <sup>2</sup> )	Ratio	Size (10 <sup>3</sup> Km <sup>2</sup> )	Ratio	Size (10 <sup>3</sup> Km <sup>2</sup> )	Ratio
Europe	7,572	1	15,846	1	23,418	1
North America	19,470	2.6	13,122	0.8	32,592	1.4
South America	12,969	1.7	4,152	0.3	17,121	0.7
Africa	28,381	3.7	1,396	0.1	29,777	1.3
Total	68,392	9.0	34,516	2.2	102,908	4.4

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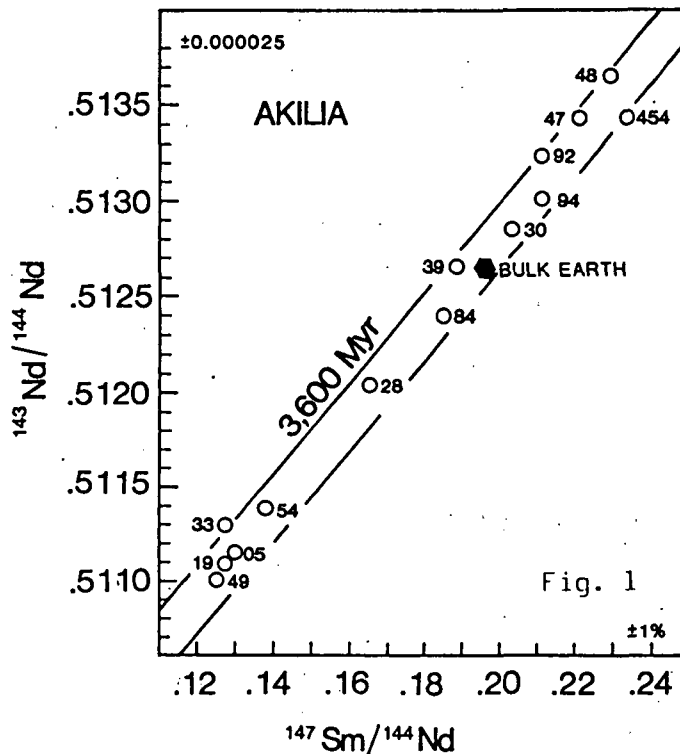
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**SIGNIFICANCE OF THE Sm-Nd ISOTOPIC SYSTEMATICS OF THE AKILIA ASSOCIATION;** G. Gruau\*, A. Nutman\*\*, and B.M. Jahn\*, \*CAESS-CNRS, Université de Rennes, Institut de Géologie (France), \*\* Geological Survey of Greenland, Copenhagen, (Denmark)

*Samarium Neodymium*  
Sm-Nd isotopic analyses were carried out on fourteen samples of basic to ultrabasic metavolcanics from several enclaves of the Amitsoq gneisses ( $T \approx 3,700$  Ma). Field observations suggest that all the analyzed rocks belong to the pre-Amitsoq Akilia Association. Consequently, a minimum age of 3,700 Ma is postulated for the emplacement of their protoliths.

When all the data points are put together in a conventional isochron diagram, no clear isochron relationship can be discerned. However, they seem to fall within a band broadly corresponding to an age of 3,600 Ma (Fig. 1).

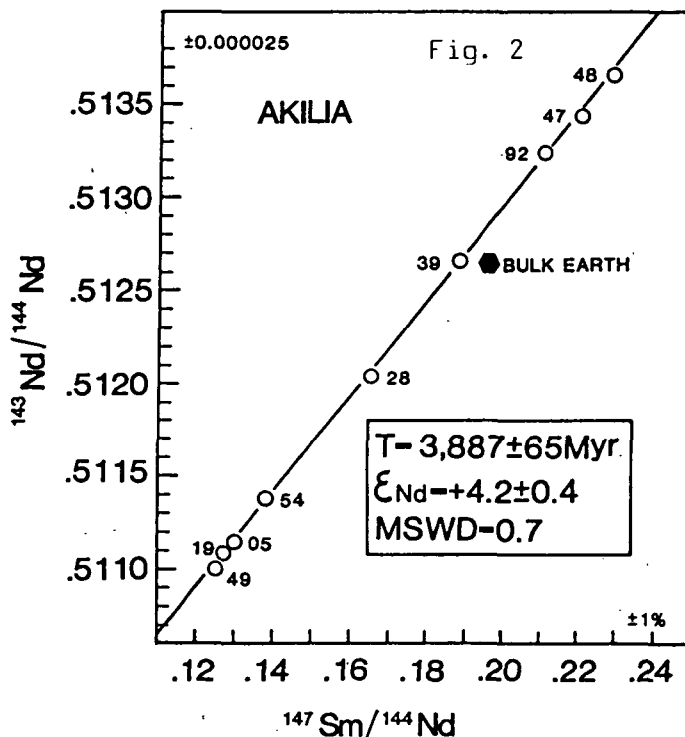


The isotopic results are difficult to interpret satisfactorily. We offer in the following two contrasting interpretations: (1) data scatter as a result of open system behavior; (2) data scatter due to a melange of data sets defining two distinct isochrons.

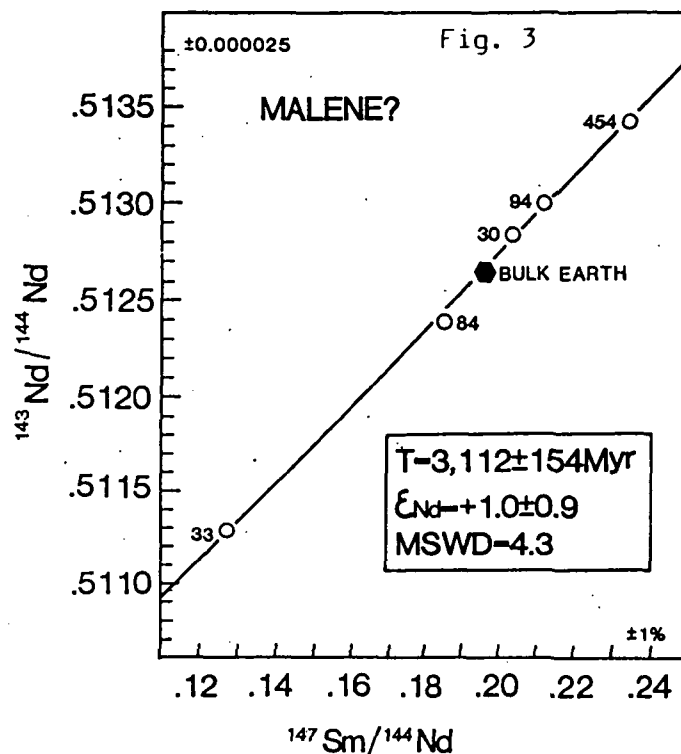
**(1) Open System Interpretation:** Disturbance of Sm-Nd systems in high grade metamorphic terrains has been documented (1,2). The basic-ultrabasic enclaves of the Akilia Association have undergone very complicated metamorphic history (3,4,5). At least two prograde (3,600 Ma, 2,800 Ma)

and one retrograde (2,550 Ma) metamorphic episodes have been recognized (6, 7). The 3,600 Ma metamorphism has clearly affected the area from where the present samples were collected. Although it is not certain that the Sm-Nd systems of the studied samples have been opened, isotopic disturbance in these repeatedly metamorphosed enclaves is likely. Furthermore, because the data array seems to be parallel to the reference isochron of 3,600 Ma, it appears that the hypothesized open system might be concurrent with the 3,600 Ma granulite facies metamorphism (7). Accordingly, the scattering of data points (Fig. 1) could be due to incomplete rehomogenization of Nd isotopes during the granulite facies metamorphism. Alternatively, the scattering might represent additional disturbances during later metamorphic episodes.

**(2) Two-Isochron Interpretation :** Assuming no post-magmatic isotopic disturbances have occurred, the present data sets could be resolved into two well-defined isochrons : (1)  $T = 3,887 \pm 65$  Ma,  $\epsilon_{\text{Nd}}(T) = +4.2 \pm 0.4$ , (Fig. 2) ; (2)  $T = 3,112 \pm 154$  Ma,  $\epsilon_{\text{Nd}}(T) = +1.0 \pm 0.9$ , (Fig. 3). In other words, the scattering of data points shown in Fig. 1 was a result of mixed populations representing a set of Akilia rocks and a set of post-Amitsoq Malene metavolcanics respectively.







The grouping in Figs. 2 and 3 was made by visual judgement and is certainly subject to debate. Two sets of arguments could, however, support this interpretation. First, the Akilia association and the younger Malene Supracrustals are known to have very similar lithologies (3,8). Both have been severely deformed and folded during later tectono-metamorphic episodes, and are now intimately juxtaposed (9). Recognition of the two supracrustal sequences in such highly deformed areas may not be easy. Hence it is possible that samples of different sequences have been collected and analyzed. Second, the two "isochron" ages correspond reasonably, may it be accidentally, to the anticipated events for the volcanisms of the Akilia Association ( $T \geq 3,800$  Ma) and the Malene Supracrustals ( $T \approx 3,100$  Ma, 4).

At present, we have no preference over the two alternative interpretations. Should the second interpretation be proven correct, both the age ( $3,887 \pm 65$  Ma) and the high positive  $\epsilon_{\text{Nd}}$  value (+4) would be very significant in the understanding of the early chemical evolution of the terrestrial mantle. High positive  $\epsilon_{\text{Nd}}$  values (+2 to +3.5) have also been reported for several units of the Isua Belt ( $T \approx 3,800$  Ma, 10). All these data suggest that at least some parts of early mantle have been highly depleted and isolated soon following the accretion and very early differentiation of the Earth about 4,500 Ma ago.

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AGE AND ORIGIN OF GNEISSES SOUTH OF AMERALIK, BETWEEN  
KANGIMUT-SANGMISSOQ AND QASIGIANGUIT.

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Q9526/50

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Gneisses which crop out along the southern coast of Ameralik between Kangimut-sangmissoq and Qasigianguit have been the subject of long-standing controversy concerning their relationship to the early Archaean Amitsoq gneisses of the Godthaab district.

On the basis of field observations, it has been argued that gneisses at Kangimut-sangmissoq and Qasigianguit are correlatives of the early Archaean Amitsoq gneisses. However, we believe that isotopic data on the K-s-Q gneisses are incompatible either with the direct correlation of K-s-Q and Amitsoq gneisses or with the proposition that the K-s-Q gneisses could have been substantially derived from Amitsoq gneisses by magmatic or metamorphic reworking during a later tectonothermal event.

Fig.1 shows a Sm-Nd isochron diagram on which are plotted the whole-rock analyses of six samples of the K-s-Q gneisses and eleven samples of Amitsoq gneisses. The K-s-Q gneisses define a  $2825 \pm 125$  Ma. isochron, with  $\epsilon_{Nd(I)}$  of +2.2 units. The Amitsoq gneisses define a  $3627 \pm 48$  Ma. isochron, with  $\epsilon_{Nd(I)}$  of +1.7 units. The Sm-Nd isotopic data for the two rock-units are clearly quite distinct and do not permit any simple genetic relationship between the gneiss suites. The positive  $\epsilon_{Nd(I)}$  value demonstrates the lack of any identifiable component of ancient continental crustal Nd in the K-s-Q gneisses.

Fig.2 shows a Rb-Sr whole-rock isochron diagram for six samples of K-s-Q gneisses. These define a  $2770 \pm 185$  Ma. isochron, with an initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of  $0.70195 \pm 54$ . The K-s-Q gneisses are generally very depleted with respect to Rb. The six samples analysed for this work are those with the highest Rb concentrations. The Sr isotope evolution diagram (fig.3) shows the bulk-earth evolution line terminating at  $\otimes$ , the average Amitsoq gneiss growth line, and the growth lines for the K-s-Q gneisses with the least and most radiogenic Sr. Average Amitsoq gneiss at present erosion level had Sr far more radiogenic than K-s-Q gneisses at ca.2770 Ma. Such Amitsoq gneisses could not be the parent material from which K-s-Q gneisses were formed. Indeed, almost all analysed Amitsoq gneisses would have had  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios greater than ca.0.70195 at ca.2770 Ma. Models requiring very severe early Archaean Rb-depletion, followed by late Archaean re-introduction of Rb could be proposed to explain K-s-Q gneiss Sr isotope evolution in order to permit an early Archaean crustal residence age for the protoliths of the K-s-Q gneisses. However, such models cannot be made consistent with requirements for the Nd and Pb isotopic evolution, and they should therefore be discounted.

AGE OF GNEISSES AT KANGIMUT-SANGMISSOQ & QASIGIANGUIT.  
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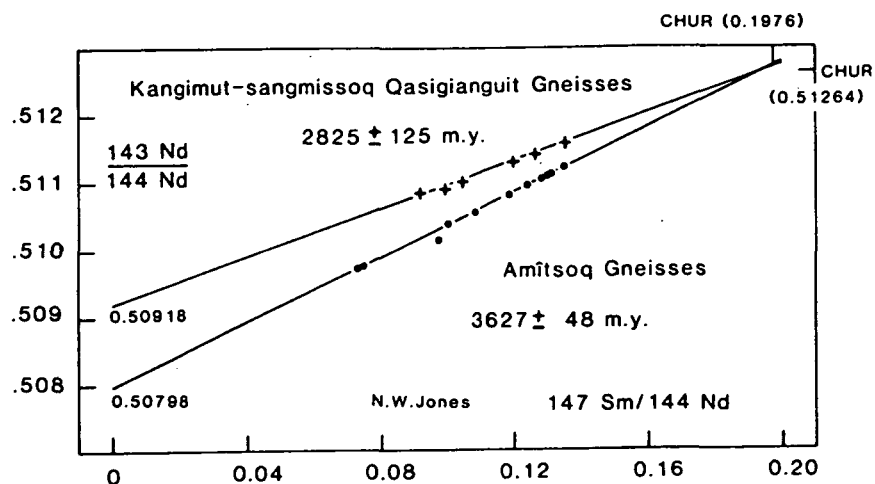


Fig.1. Sm-Nd isochron diagram for the Amitsoq and the Kangimut-sangmissoq & Qasigianguit gneisses.

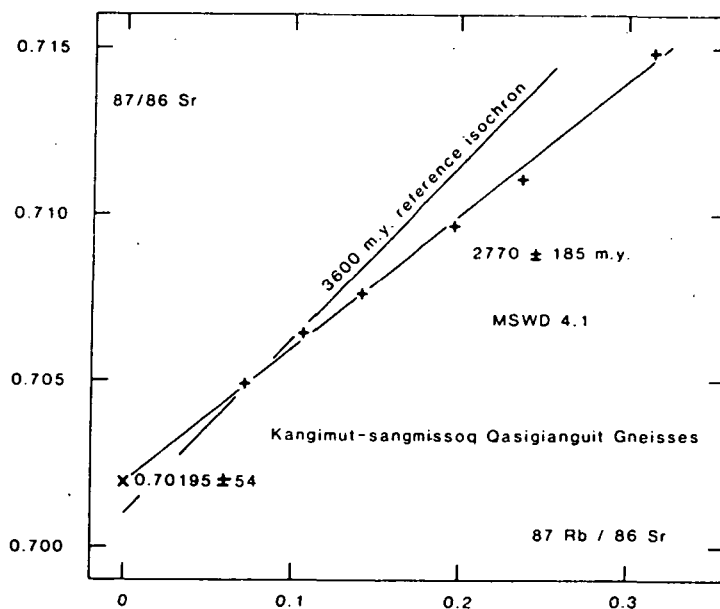


Fig.2. Rb-Sr isochron diagram for the Kangimut-sangmissoq & Qasigianguit gneisses.

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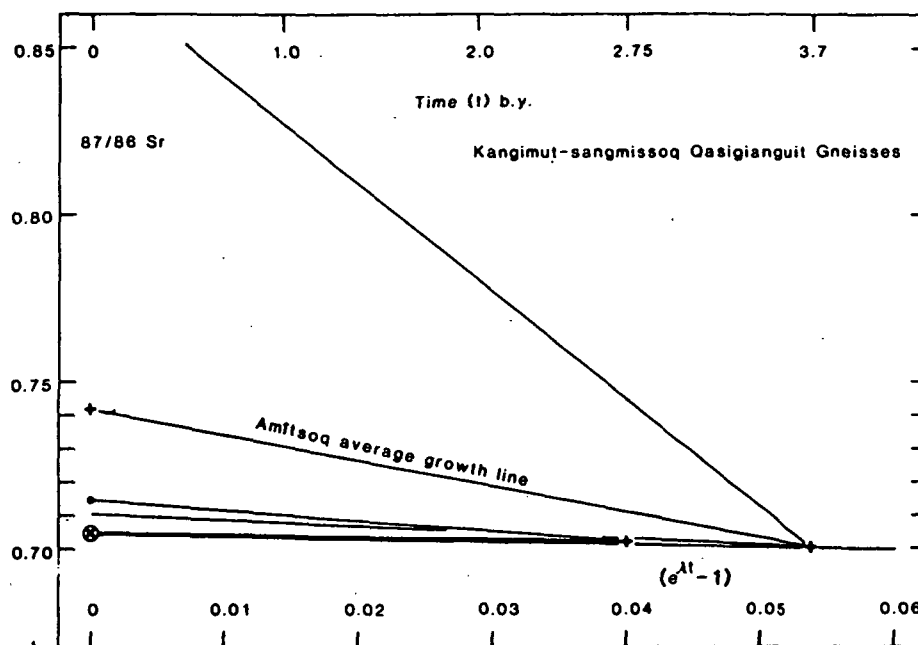


Fig. 3. Sr isotope evolution diagram for the Kangimut-sangmissoq & Qasigianguit gneisses.

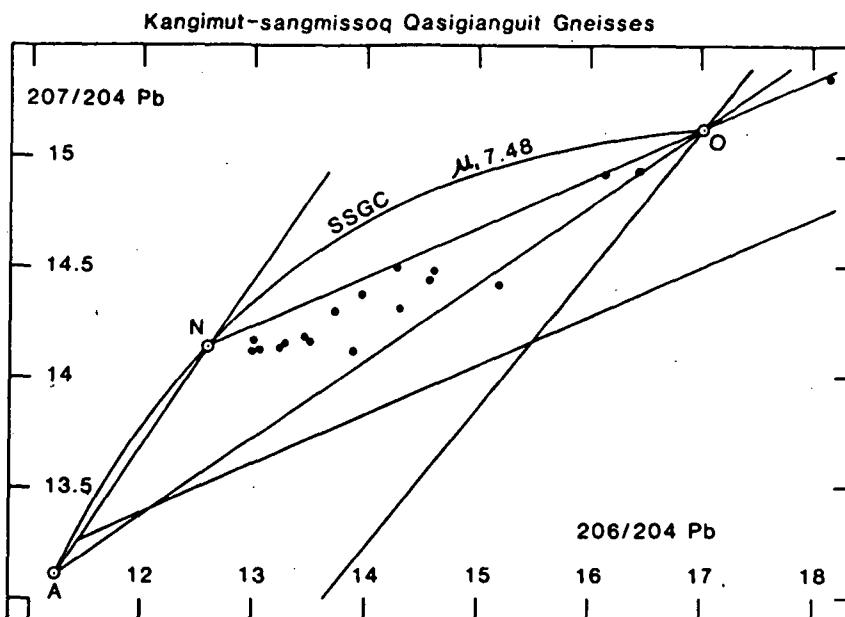


Fig. 4. Pb isotope evolution diagram for the Kangimut-sangmissoq & Qasigianguit gneisses. For details of the interpretative framework see text and ref. (1).

AGE OF GNEISSES AT KANGIMUT-SANGMISSQ & QASIGIANGUIT.  
Jones, N.W., Moorbath, S. & Taylor, P.N.

Fig. 4 is a Pb-Pb diagram in which the whole-rock isotopic analyses of eighteen K-s-Q gneisses are plotted. The Pb isotope data are interpreted within the framework of the crustal contamination model presented by Taylor et al. (1) for Nûk gneisses emplaced into or through Amîtsoq gneisses. AND is the single-stage growth curve for a system with a  $\mu$  value of 7.48. A is the model initial Pb of Amîtsoq gneisses at ca. 3700 Ma., and N the model initial Pb of ca. 2900 Ma. old Nûk gneisses which did not suffer contamination due to interaction with Amîtsoq gneisses. NO is the present-day isochron line occupied by uncontaminated Nûk gneisses. In the Godthaab district most of the late Archaean intrusive rocks show clear Pb isotopic evidence of interaction with Amîtsoq gneisses, i.e. their Pb isotopic analyses plot below NO. The K-s-Q gneisses also show such evidence for contamination with Amîtsoq-type Pb, although very few show severe contamination effects, and most have a very large proportion of their initial Pb from a juvenile source at ca. 2770 Ma. : i.e. they are generally less contaminated than most Nûk gneisses.

Two K-s-Q gneisses plot close to the extension of the present-day array of Amîtsoq gneiss Pb data (AO in fig. 4.), but much closer to O than the analysed Amîtsoq gneisses from the Godthaab district, which occupy the lower third of AO. It is highly improbable that these two samples actually represent Amîtsoq gneisses : they would be very unusual in having suffered much less severe U-depletion than any analysed Amîtsoq gneisses from the Godthaab district. Consequently it is very unlikely that these two samples should be interpreted differently from other K-s-Q samples.

We conclude that the K-s-Q gneisses represent an addition of substantially juvenile mantle-derived material to the Archaean craton of West Greenland during late Archaean times. Some of the parent magmas have undergone interaction with older crust, as indicated by the Pb isotope evidence for contamination with Amîtsoq-derived Pb. However, the positive  $\epsilon_{Nd(I)}$  value for the K-s-Q gneisses firmly rules out any significant material contribution from the Amîtsoq gneisses to the K-s-Q gneisses.

## Reference.

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This abstract is published with the kind permission of the Director of the Geological Survey of Greenland.

ARCHEAN METAMORPHIC SEQUENCE AND SURFACES, KANGERDLUGSSUAQ FJORD,  
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Introduction: The characteristics of Archean metamorphic surfaces and fabrics of a mapped sequence of rocks older than ca. 3000 Ma [1] provide information basic to an understanding of the structural evolution and metamorphic history in Kangerdlugssuaq Fjord, east Greenland. This information and the additional results of petrologic and geochemical studies [2] have culminated in an extended chronology (Table 1) of Archean plutonic, metamorphic, and tectonic events for Kangerdlugssuaq Fjord [3,4]. This paper considers the basis for the chronology and especially the nature of the metamorphic fabrics and surfaces in the Archean sequence. The surfaces, which are planar mineral parageneses, may prove to be mappable outside Kangerdlugssuaq Fjord, and if so, they will be helpful in extending the events that they represent to other Archean sequences in east Greenland. The surfaces will become especially important reference planes if the absolute ages of their metamorphic assemblages can be determined in at least one location where strain was low subsequent to their recrystallization. Once an isochron is obtained, the dynamothermal age of the regionally identifiable metamorphic surface is determined everywhere it can be mapped.

Pre-3000 Ma Gneisses: The reconnaissance mapping (1:500,000) over the greater area of Kangerdlugssuaq Fjord [5], and the more detailed mapping (1:20,000) of this study (Fig. 1) along Watkins Fjord indicate that there are two distinct generations of granitoid gneisses. The distinction between the two is mainly structural. The older gneisses are banded migmatitic rocks containing thin biotite-rich and/or hornblende-rich parts veined and fragmented by quartz-feldspar-rich layers. The mafic bands occur as faded, "ghost-like" remnants within the bands and layers of quartz-feldspar. Early folds involving mafic paleosome and quartzofeldspathic neosome are refolded.

Supracrustal Sequence: The supracrustal rocks of this study are in apparent tectonic contact with the older gneisses, and both these rock groups are intruded by the ca. 3000 Ma calc alkaline gneiss suite. The mapped character of the supracrustal sequence is that of very narrow and deformed, elongate belts that are gradationally xenolithic in the ca. 3000 Ma gneisses. Outcrop patterns of belts are partly the result of folding (Fig. 1). Elongate belts of character similar to those of the supracrustal rocks in Kangerdlugssuaq Fjord extend south nearly 300 km to Angmagssalik [5].

Metaclastic rocks are abundant in the belts of the map area. The common types are biotite-bearing quartz-feldspar schists, micaceous quartzites, garnet-biotite schists, and quartz-sillimanite-biotite schists ( $\pm$ cordierite  $\pm$  garnet). Amphibolites are nearly as abundant as the metaclastic rocks; hornblende and plagioclase are finely banded on a mm scale and locally have gradational relations with garnet-biotite schists. Thin bands of iron-silicate-bearing quartzites or metacherts have persistent interlayered association with the amphibolites. The main iron-silicate in the quartzites is almandine, but hornblende is commonly present, there are subordinate iron-ores, and there is rare occurrence of hypersthene and fayalite.

Ultramafic Rocks: Elongate, pod-like ultramafic bodies of variable dimensions commonly measured in m, but up to 0.5 km long and 100 m thick, are widespread in the supracrustal sequence. Although greatly modified by later deformation, discordant contact relationships with the older gneisses and supracrustal rocks provide evidence that the ultramafic rocks are remnants of elongate dikes/sills. Mapped metamorphic surfaces, structures, and fab-

rics in the supracrust and older gneiss show that intrusion of ultramafic liquid was earlier than regional metamorphism/deformation common to all these rocks. The ultramafic rocks are largely amphibole-bearing peridotites with olivine, orthopyroxene or clinopyroxene (but not both), green hercynitic, brown, and iron-chrome spinels, talc and chlorite.

3000 Ma Gneisses: The younger gneisses from which the  $2980 \pm 20$  Ma Pb-Pb isochron [1] was obtained are polyphase intrusive rocks with compositional range tonalite to granodiorite, adamellite and granite [2]. These gneisses are the most voluminous Archean rocks in the area, and intrude supracrustal belt rocks and migmatitic gneisses. Directional fabrics of the rocks are strong but of variable character, and many rocks are foliated.

Significance of Fsp-Stage and Fgn-Stage Folds: Archean surfaces folded by Fsp-stage folds are 1) Sbgm migmatitic banding in the older gneisses; 2) Suml compositional banding generally at a high angle to and frequently transposed by 3) Scl metamorphic cleavage in the ultramafic rocks; 4) Ssp metamorphic foliation and nearly parallel compositional banding in the supracrustal rocks. Fsp-stage folds are not found in the 3000 Ma gneisses (Table 1). Strong deformation during and following intrusion of the younger gneisses developed in them penetrative fabrics Sgn and nearly parallel trends with Ssp, Scl, and Sbgm surfaces of the intruded rocks. Nevertheless, evidence is preserved for angular intrusive discordance just at the contacts between intrusive and intruded rocks. The gneisses with Sgn fabrics are folded by only the Fgn-stage folds which also affect the Fsp-stage folds and all the Fsp-folded metamorphic and migmatitic surfaces (Table 1).

The Sbgm Surface and its Relation to Ssp: Of earliest generation in this region may be the Sbgm surface of migmatitic banding. Biotite-rich and/or hornblende-rich bands now only mm thick are clearly fragmentary remnants of some pre-existing, presumably supracrustal rocks, and constitute the paleosome. The Sbgm and Ssp surfaces are both affected by Fsp-stage and Fgn-stage folds. However, on northwest Kraemers Island the Ssp and Sbgm surfaces of supracrustal belt biotite-garnet schist and migmatite gneiss, respectively, are discordant: here, near their contact, discrete and streamlined, lenticular bodies of schist are enclosed by gneiss and their respective surfaces share Fgn-stage folds. The interpretation is that the discordance is tectonic and that the lenticular schist bodies are tectonic slivers formed as a result of thrust faulting during the later stages in the development of a fold nappe. According to such a model the Sbgm surface must be older than tectonic juxtaposition but the relative age of it with respect to the surface Ssp cannot be determined.

The Ssp Surface in Supracrustal Belt Rocks: The prominent penetrative fabric Ssp in the supracrustal belt rocks consists of planar orientations of the minerals biotite, hornblende, platy quartz, and feldspar. The Ssp schistosity is parallel or subparallel to compositional banding which consists of alternating layers of quartz, or quartz-feldspar, or feldspar and segregations of a variety of Fe-Mg-Al-silicates and sillimanite. Because they have essentially the same orientation, and there is no consistent evidence for transposition of one by the other, schistosity and compositional banding are not distinguished and both are referred to as Ssp foliation. The parallel growth of planar minerals and their segregation into roughly parallel bands were in response to syntectonic recrystallization possibly along axial planar surfaces at an earlier stage. Subsequently, minerals of Ssp-stage fabrics were folded about Fsp-stage hinges earlier than or during tectonic juxtaposition with the migmatite gneisses. Maximum metamorphism associated with the Ssp surface in pelitic and semipelitic rocks is constrained only in



terms of the divariant association of sillimanite-biotite-quartz above the breakdown temperature of muscovite-quartz (upper amphibolite facies). This is because the assemblages of the supracrustal rocks are polymetamorphic and recrystallization following development of Ssp assemblages overlapped their stability field while preserving Ssp assemblages and fabrics.

Scl and other Surfaces in Ultramafic Rocks: Observations from many locations indicate that there are three kinds of fabrics recognizable in the ultramafic rocks: 1) compositional layering Suml in which occasional iron-chrome-oxide-rich bands alternate with olivine-richer and pyroxene-richer bands that are frequently several cm to tens of cm thick; 2) metamorphic cleavage Scl which transposes and frequently obliterates the earlier compositional layering; 3) reaction selvages Surs which conform generally to the pod-like shape of the bodies and are several cm to tens of cm thick separating the ultramafic rocks from the adjacent gneisses and gneiss-intruded contact with supracrustal rocks. The evidence is good that the order given here is also the order in which the fabrics were acquired. Field evidence from northwest Kraemers Island suggests that perfectly parallel Scl cleavage and Ssp foliation are equivalent in ultramafic and supracrustal rocks, respectively, and are later than the discordant contact between the two rock types. Assemblages which form the Scl surface correspond regionally to metamorphism in the T-P field of tremolite-chlorite peridotite [6]. However, the assemblages are polymetamorphic and post-Scl assemblages Surs are at higher grade.

The Sgn Surface: The penetrative foliation Sgn in the ca. 3000 Ma gneisses consists of flattened-elongated quartz-feldspar, parallel biotite flakes, and elongated hornblende. The assemblages are consistent with subsolidus recrystallization above the stability of muscovite+quartz but below the stability of biotite+quartz and hornblende+quartz in rocks of compositional range tonalite to granite. Sgn fabrics are discordant with and later than Scl, Ssp, and Sbgc cleavages and foliations.

Post-Sgn Effects: Porphyroblastic minerals of supracrustal rocks incorporate minerals of the Ssp surface and overlap their stability fields. Locally the porphyroblastic minerals have measured alignment in outcrop parallel with Fgn axes and transpose Ssp foliation in the hinge areas of Fgn folds. The porphyroblastic assemblages of ultramafic rocks are those of previously described Surs selvage assemblages. Preferred orientations of the porphyroblastic assemblages aren't obvious, but the Surs selvage surfaces have boudinage elongation parallel to Fgn axes. In the 3000 Ma gneisses, annealed mylonitic flaser structure emphasized by coarse feldspar augen also has elongation parallel to Fgn axes locally transposing Sgn foliation through Fgn fold hinges. None of the post-Sgn effects just described is penetrative. Ssp, Scl, and post-Sgn porphyroblastic assemblages together constitute polymetamorphic assemblages which at maximum grade are represented by 1) chlorite = orthopyroxene + olivine + green spinel + vapor [7] in peridotites, and by 2) biotite + sillimanite + quartz = cordierite + garnet + K-feldspar + vapor/liquid [8] in metapelites.

Summary and Conclusions: An effective method of documenting isotopically disturbed rocks older than the ca. 3000 Ma Pb-Pb isochron obtained for the voluminous calc alkaline gneisses in Kangerdlugssuaq Fjord is to map the metamorphic surfaces and fabrics of all the Archean rocks. A key to an understanding of Archean chronological relations (Table 1) is the recognition of Fsp-stage folding that is earlier than formation of the metamorphic surface Sgn in the ca. 3000 Ma gneisses. Important features of the earlier metamorphism are the well preserved, and predominant Ssp and Scl metamorphic surfaces which record a high grade dynamothermal event older than intrusion of

the ca. 3000 Ma gneisses. The interpretation here is that the final high grade metamorphic event overlapped with the heating associated with emplacement and continuing deformation (Fgn) of the youngest gneisses. The Sgn fabric in those gneisses is interpreted to be the result of synkinematic crystallization and/or subsolidus flow at temperatures above about 600°C [9,10] in a recumbent tectonic regime [11,12]. Flow fabrics equivalent to Sgn are absent in the supracrustal, ultramafic, and older gneissic rocks because stress as a component of lithostatic pressure effected pervasive movement in only the hot plastic or semi-liquid calc alkaline nappes.

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Table 1. Chronology of Archean events in Kangerdlugssuaq Fjord

7. Isoclinal upright Fgn folding of the ca. 3000 Ma calc alkaline gneiss suite, Ssp, Scl, Sbg surfaces; local transposition of Sgn and Ssp foliation through Fgn hinges during final high grade equilibration of Archean rocks.
6. Extended period of intrusion, sheet-like pulses of calc alkaline mantle-derived magma invade tectonically interlayered supracrust and migmatitic gneisses. Planar and linear penetrative Sgn fabrics by synkinematic or sub-solidus flow of plutonic rocks forming flattened-aligned quartz, feldspar, and biotite+hornblende.
5. Fold nappes form resulting at some early stage in tight recumbent Fsp-stage folds of Ssp and Sbg surfaces; at a later stage there is thrusting and tectonic interleaving of the recumbent folded sequence.
4. Syntectonic regional metamorphism of intermediate baric type forms penetrative Ssp foliation (supracrust) and Scl cleavage (ultramafic rocks).
3. Intrusion of ultramafic magma forming elongate dikes in supracrust and migmatitic gneisses; crystal settling-differentiation of magma forms Suml compositional layers (iron-chrome-oxides, olivine, and pyroxenes).
2. Deposition of supracrustal rocks apparently on granitoid basement gneisses. Accumulation of sedimentary debris with very aluminous interlayers (to 25 wt % Al<sub>2</sub>O<sub>3</sub>) was apparently in a basin of moderate depth with nearby volcanic source which periodically erupted basic magma; associated chemical precipitation of silica forms chert beds with localized iron-oxides-sulfides.
1. Intrusion of granitoid magma into biotite and hornblende-bearing layered and presumably metamorphosed rocks results in secondary migmatitic layers in which there is alternating quartz-feldspar and hornblende/biotite identifiable now as the surface Sbg.

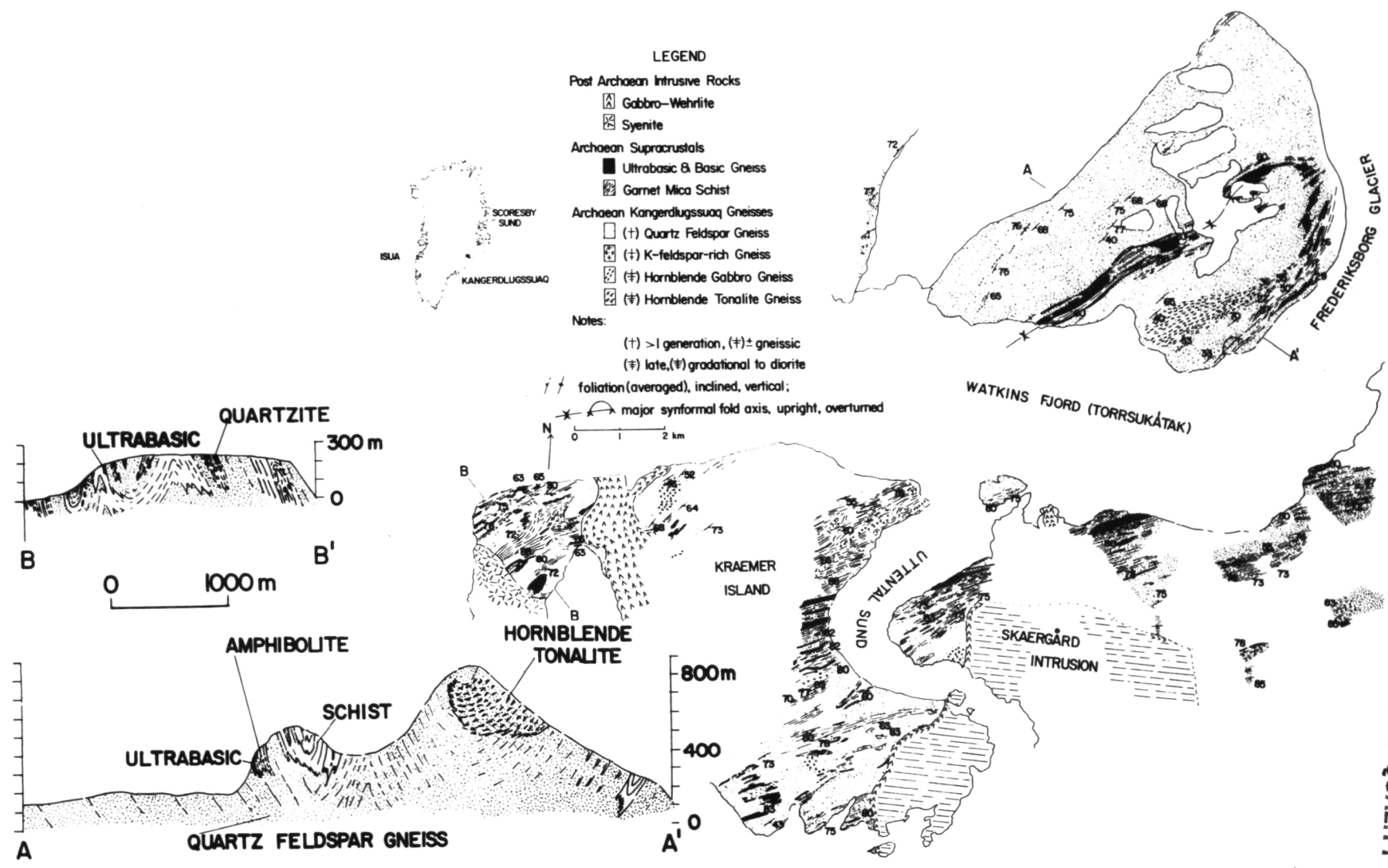


Fig. 1. Geology of the inner part of Kangerdlugssuaq Fjord in the Watkins Fjord area.

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METAMORPHOSED ULTRAMAFIC ROCKS IN EAST GREENLAND: M.A. Kays, and M. J. Dorais\*, Department of Geology, University of Oregon, Eugene, OR 97403 (\*University of Georgia, Athens, GA 30602)

Introduction: Ultramafic rocks have widespread distribution as elongate pod-like bodies in association with supracrustal belt rocks and granitoid basement gneisses older than ca. 2900 Ma (Fig. 1) in east Labrador [1,2], west Greenland [3,4,5], east Greenland [6,7], and northwest Scotland [8,9]. The bodies have locally preserved discordant contacts with the supracrustal belt rocks [5,6,7], and have strong compositional banding with cm thick layers enriched in chrome-iron oxides, olivine, pyroxene, or some combination of these minerals. Some ultramafic bodies also contain layers of gabbro [7,8]. The ultramafic rocks are not uncommon as xenoliths in Archean gneisses with age of ca. 2900 Ma or younger; the xenoliths occur with size ranging from a few cm diameter to large rafts more than 100 m long. Analyzed suites of the pod-like Archean ultramafic bodies have compositional characteristics similar to komatiite-tholeiite suites of Archean greenstone belts [8,10,11], or to the basal parts of layered intrusions and constructional sequences of similar character [12]. In the indexed localities of Fig. 1 the major period of emplacement of the ultramafic rocks was earlier than the voluminous generation of calc alkaline magma at ca. 2700-2900 Ma [13,14]. Thus, the occurrence of the ultramafic rocks may be an important marker in documenting the distribution of Archean rocks older than ca. 2900 Ma in the craton of the North Atlantic region.

This paper summarizes compositional and mineralogical characteristics of Archean ultramafic rocks in Kangerdlugssuaq Fjord (Fig. 1): the first provide information important to understanding the primary character of the rock suite, whereas the latter provide data necessary to determine conditions of their equilibration during the latest metamorphism. Field characteristics and documentation for the occurrence and probable emplacement history of the ultramafic rocks are given in a companion paper [7]. The two kinds of information will be of value in determining the affinity of the suite to similar Archean rocks in other areas of the North Atlantic craton.

Whole Rock Compositional Characteristics: Major element oxides of the ultramafic rocks have decreasing abundance with respect to increasing MgO contents, but Ni shows strong positive variation rising to nearly 1800 ppm in MgO-enriched rocks (Fig. 2). Cr contents in samples that don't have oxide segregation are variable and only a crude pattern is recognizable with respect to MgO. The highest Cr content measured is about 5500 ppm in a rock with the highest measured MgO content (34 wt.%); otherwise, Cr contents range from about 1600 to 3500 ppm rising to the higher value in rocks of intermediate MgO content (ca. 25 wt.%). Analyses of amphibolites associated with the ultramafic rocks in the supracrustal belts are plotted in Fig. 2, but the relationship of amphibolites and ultramafic rocks is not clear in Kangerdlugssuaq Fjord. REE contents of three ultramafic rocks from Kangerdlugssuaq Fjord have chondrite normalized plots showing enrichment in these trace elements similar to komatiites [11], but are in strong contrast to the patterns of depletion recognized in alpine peridotites (refractory mantle lherzolites, harzburgites, and dunites) [15] shown for comparison (Fig. 2).

To test the hypothesis that the regular major oxide compositional variations and the locally preserved surface of compositional layering Suml [7] are consistent with crystal fractionation of basic magma, plots of  $TiO_2$  (wt. %) and Y (ppm) vs Zr (ppm) in ultramafic-mafic rocks were reproduced by calculated Rayleigh fractionation of olivine, pyroxenes, hornblende, and plagioclase.

clase (Fig. 3). In the calculations, distribution coefficients ( $K_D$  = mineral/liquid) were used consistent with crystallization of minerals from basaltic or picritic liquids [16]. The trend lines, when viewed in comparison with the major element contents of the ultramafic rocks, are consistent with olivine fractionation ( $\pm$ pyroxenes). Irvine [17] has also demonstrated that in basic or picritic melts crystallization follows a predictable path depending on mineral/melt  $K_D$  values and magma  $f_{O_2}$ . Thus, if olivine crystal fractionation was the mechanism responsible for forming the variety of Kangerdlugssuaq Fjord ultramafic rocks, Al would have been effectively excluded to the melt during the process. During such crystallization and exclusion, Al/Mg+Fe<sup>2+</sup> changes gradually, the fractionation path changing little with additional separation of the pyroxenes. Ultimately, Al exclusion is drastically altered by separation of the feldspars. The path of Kangerdlugssuaq Fjord ultramafic rocks seems consistent with such a model (Fig. 3), although it seems doubtful that the stage of feldspar separation occurred during fractionation of the ultramafic sequences.

Metamorphism and Mineral Chemistry of the Ultramafic Rocks: Diagnostic assemblages in the polymetamorphic ultramafic rocks at the highest grade are the previously described Surs assemblages [7] containing olivine+orthopyroxene+green spinel+chlorite+amphibole. Textural evidence in the field and in thin section is that there was modification of the Scl assemblage (metamorphic cleavage) during the last recrystallization episode at ca. 2900 Ma [18]. We assume here that the assemblage reflects equilibrium recrystallization that was in part mimetic after the Scl assemblage. Mimetic recrystallization was perhaps aided because conditions of the final event greatly overlapped those of the earlier episode and because a penetrative fabric did not form in the ultramafic or adjacent supracrustal rocks during the final event. The assemblage indicated above is approximately equivalent to the sillimanite zone amphibolite facies boundary with the granulite facies [19], and is consistent with the assemblage quartz+biotite+sillimanite+cordierite+garnet+K-feldspar in the metapelites. The two assemblages in ultramafic and pelitic rocks, respectively, are consistent with the equilibria 1) chlorite = 2 orthopyroxene+olivine+spinel+vapor, and 2) quartz+sillimanite+biotite = cordierite+garnet+K-feldspar+liquid/vapor [19,20].

The equilibrium P-T curve for equation (1) calculated recently [21] gives a temperature of about 770°C at 5 kbars for pure Mg end member thermodynamic data where water pressure and total pressure are the same. Recalculation of the curve to include compositions of analyzed minerals in sample KWF72 (Table 1) gives a temperature of about 25°C lower at the same pressure. Thus, the effects of Fe-Mg and other substitutions in the minerals of Surs ultramafic assemblages reflect conditions of equilibration not greatly different from Mg end member reactions. Results of olivine-spinel geothermometry in five ultramafic rock samples with an assemblage close to that of (1) indicate continued re-equilibration during cooling following the main recrystallization.

Some additional data for the minerals analyzed by electron microprobe in samples containing green spinel+orthopyroxene+olivine+amphibole $\pm$ chlorite in Kangerdlugssuaq Fjord ultramafic rocks are given in Table 1. We also note that olivine and pyroxenes have nearly identical compositional range and variation in the five rock samples analyzed. Fo and En contents in olivines and pyroxenes vary from about 75 to 87 mol %; these compositional variations in the minerals are consistent with bulk compositional variations of their host rocks (MgO varies from 20 to 32 wt%). The green spinels are aluminous and Fe-rich, but with variable Cr contents; compositional variations on an atomic

basis are:  $Y_{Al} = 0.86$  to  $0.96$ ;  $Y_{Cr} = 0.04$  to  $0.14$ ;  $X_{Fe} = 0.39$  to  $0.58$ ;  $X_{Mg} = 0.42$  to  $0.61$ . We note too that the amphiboles are colorless pargasite and greenish edenitic hornblende. Analyzed chlorite of KWF-72 is clinocllore according to the nomenclature of Hey [22].

**Summary and Conclusions:** Studies in a number of localities in the North Atlantic region including Kangerdlugssuaq Fjord indicate that elongate Archean ultramafic bodies have intrusive contacts with rocks of supracrustal sequences that are mostly older than 2800-2900 Ma. Thus, the ultramafic rocks may prove to be reliable markers that identify Archean crustal sections older than the voluminous accretionary magmatism at ca. 2700-2900 Ma. In some locations, as in Kangerdlugssuaq Fjord, the bodies have preserved compositional banding that is probably related to crystal accumulation or some similar magmatic process. Such layering provides another reference surface with which to "re-orient" Archean crust with respect to subsequent deformation and recrystallization. The surface, such as Sum1 in Kangerdlugssuaq Fjord, also has the potential to provide ages of primary Archean rock emplacement earlier than that of accretionary magmatism and earlier than the metamorphism of the supracrustal sequences that contain the bodies. Widespread distribution of the ultramafic bodies suggests the possibility of an important tectonic event associated perhaps with dilatational fracturing of the craton. Such an event would contrast markedly with the tectonic setting that followed and in which there was massive addition of calc alkaline magma to the Archean cratonic nucleus. Mineral assemblages of the ultramafic bodies also provide reliable markers of the temperature conditions of their metamorphic equilibration, and appear to offer proof in Kangerdlugssuaq Fjord of polymetamorphism compatible with that of the associated supracrustal sequence.

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A MODEL FOR THE BIOLOGICAL PRECIPITATION OF PRECAMBRIAN  
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As the major chemical sedimentary rock formed in the Archean and Early Proterozoic, iron-formation has been widely used as a basis for geochemical inferences about the chemistry of the early atmosphere and oceans. However, the present mineralogy of iron-formation probably better reflects diagenetic and metamorphic modifications rather than chemical attributes of the early atmosphere and oceans. On the other hand, the existence of iron-formation sequences, which may contain thousands of cubic miles of chemically precipitated iron and silica, probably does reflect on the nature of the early atmosphere and oceans. In this discussion I am restricting the term iron-formation to rocks containing roughly equal proportions of silica and iron minerals.

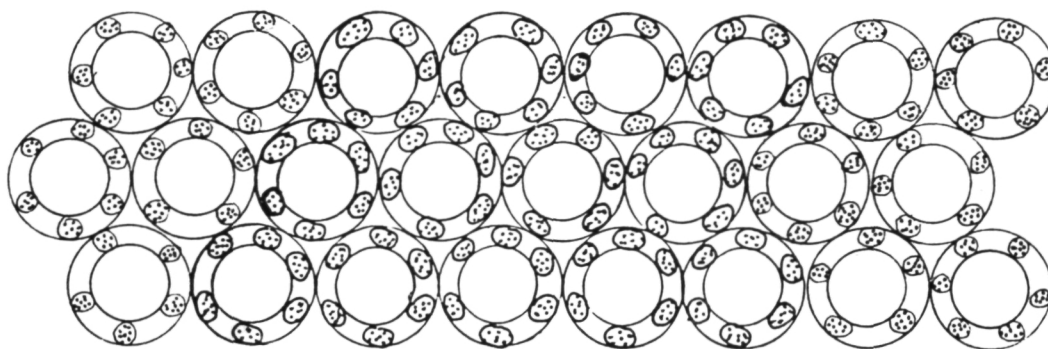
Today, under an oxygenated atmosphere and consequent oxygenated ocean, the extreme insolubility of ferric iron precludes attaining significant concentrations in a water column. Therefore, widespread cherty iron-formations do not form. A relatively oxygen-deficient atmosphere seems necessary to allow sufficient ferrous iron in solution to produce widespread iron precipitation. However, an oxygen-deficient atmosphere, with its associated reducing water column and load of ferrous iron, poses the problem of a mechanism in the Proterozoic and Archean to precipitate the iron. This would be accomplished most readily by oxidizing the relatively soluble ferrous iron to an insoluble ferric hydrate, which textural evidence and geochemical models suggest is the main precipitate.

Because iron-formations range in age from 3,800 Ga to about 1,900 Ga, and were formed in a wide variety of geological settings, it is not unreasonable to suggest that their precipitation was controlled by local conditions. These conditions would include local oxidizing conditions developed in different basins at different times and local availability of iron in these basins. The fact that the major Proterozoic iron-formations range from about 2,500 Ga for the Hamersley Range of Western Australia to about 1,900 Ga for the Lake Superior region suggests that iron-formation deposition was controlled mainly by local basin chemistry, and that atmospheric influence was minor. Furthermore, the widespread occurrence of iron-formations in the Archean also points to local basin control. While it is possible to produce a locally reducing environment with an oxygenated atmosphere today, I know of no way to produce a locally oxidizing environment with an oxygen-deficient atmosphere except by biological activity. Therefore, precipitation of the iron would be most readily accomplished by biological activity.

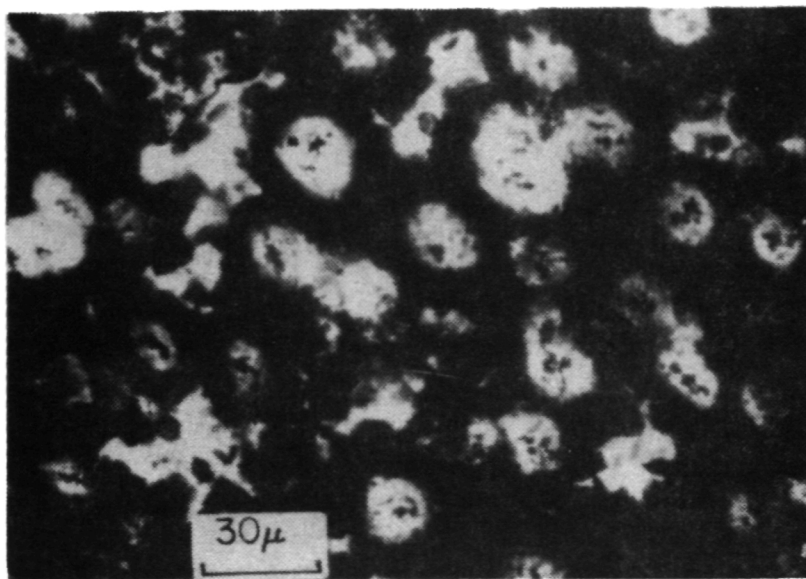
The precipitation of silica, the other major ingredient in iron-formations, is especially problematical, including disagreement on whether it is primary or secondary. While most workers assume that the chert is a primary precipitate, some (1, 2) suggest that it is a replacement of earlier calcite. Textural relations, including syneresis cracks (3), suggest that the silica is a primary precipitate. However, the mechanism of precipitation is not resolved. Although most Phanerozoic cherts are considered to be biologically precipitated (by diatoms, radiolaria and sponges), Precambrian cherts are generally considered to be inorganically precipitated because Precambrian silica-secreting organisms have not been recognized. The typical, ubiquitous association of iron and silica in iron-formations suggests that the precipitation of the two must be related, even though the

chemistry of silica is very different from that of iron. I propose to show evidence that the silica as well as the iron in iron-formations was precipitated biologically.

One of the characteristic features of iron-formation cherts is the widespread occurrence of spheroidal structures about 30  $\mu$ m in diameter that consist of a central 20  $\mu$ m sphere surrounded by a variable number of 5  $\mu$ m spheroids (4). In most cases, the spheroids are revealed by a fine hematite "dust" that outlines the structures. Although the spheroids are not present in every layer, they are present in every Proterozoic and Archean iron-formation which has not been excessively metamorphosed and sheared that I have examined. As pointed out by LaBerge (4), the structures are remarkably similar in size and morphology to the organic-walled microfossil Eosphaera tyleri, and I suggest that the spheroids are best interpreted as relict forms of that organism. If so, the details of these structures may have



Sketch of hypothetical situation of what an accumulation of Eosphaera tyleri might look like.

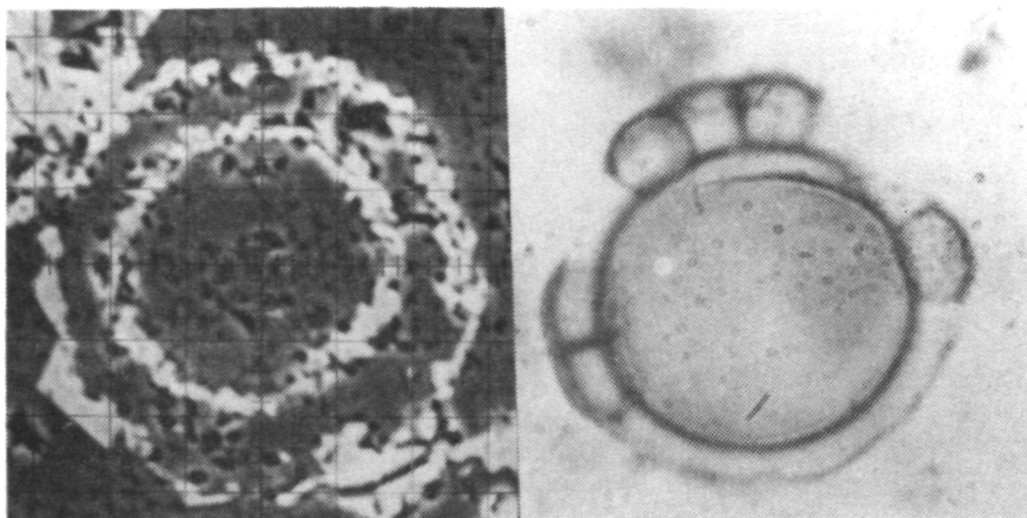


Photomicrograph of jasper with Eosphaera-like structures showing their abundance.



significant implications on the precipitation of iron-formation. First, the fact that these structures are abundantly preserved as spheroids in the cherty layers suggests that they had some rigidity, and were not simply an organic sheath, because a vast majority of organic matter in iron-formation does not retain its organic structure. Many jasper layers are virtually composed of spheroidal structures. Microscopically, the textural pattern of the *Eosphaera*-like structures suggests that the layers formed by accumulation of the spheroids. The fact that the spheroids appear to have had rigidity and to have formed the siliceous layers suggests that *Eosphaera* may have had a siliceous test. Similarly, the presence of similar structures within siliceous granules seems to attest to the durability of the spheroids. In addition, all *Eosphaera*-like structures are typically preserved by a fine hematite "dust" that colors the jasper red. The dust, then, may represent fine ferric hydrate that adhered abiotically to the organic walls of *Eosphaera*, or alternatively, it may indicate that *Eosphaera* was photosynthetic and the ferric hydrate accumulated on the membrane where oxygen was expelled (such as in modern *Volvox*), or it may be similar to the way the chemotrophic bacterium *Leptothrix* encases itself in a sheath of ferric hydrate. These two observations in the jaspers lead to the tentative interpretation that *Eosphaera* may have been a photosynthetic organism with siliceous frustules. If this interpretation is correct, it is significant regarding iron-formation and early life because these spheroids are present in Archean iron-formations including some from the 3,500 Ga old Pilbara block of Western Australia. Furthermore, the abundance of *Eosphaera*-like structures in laminated (deep water) jaspers may indicate that it was planktonic rather than benthic in life-style.

Several authors (4, 5, 6, 7) have reported that siderite in relatively unmetamorphosed iron-formations occurs as prominent spherical grains about 30  $\mu$ m in diameter. Microprobe examination of spherical siderites in Proterozoic iron-formation from the Gunflint district of Ontario reveals that they are double-walled structures remarkably similar to *Eosphaera tyleri*.



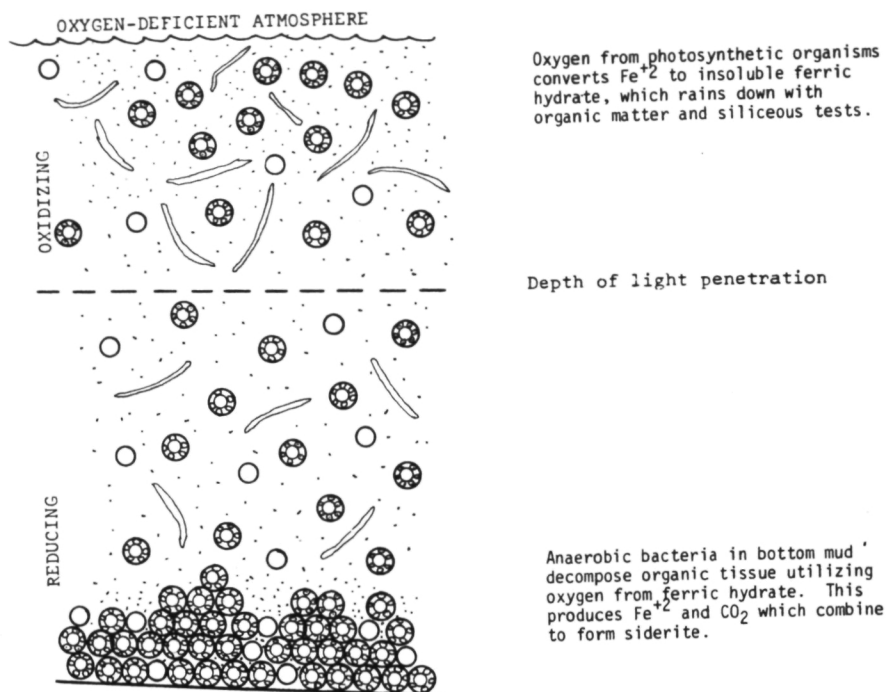
Comparison of double-walled spherical siderite (left) and *Eosphaera tyleri* (right). Siderite is white in the electron micrograph. Photos are approximately the same scale.

These double-walled, spherical siderite grains are interpreted to have formed by diagenetic alteration of primary hematite-coated varieties. Bacterial degradation of organic matter in the anoxic zone on the basin floor may have produced CO<sub>2</sub> and utilized ferric hydrate as an electron donor which reduced the iron to the ferrous state. The ferrous iron and CO<sub>2</sub> combined to form siderite "pseudomorphs" after hematite-pigmented forms involving progressive replacement of the silica. Siderite is a major mineral in some iron-formations, however, it appears to be primarily of early diagenetic origin, because siderite is part of the sedimentary fabric of the rock. The conversion of primary ferric hydrate to siderite is often incomplete, because hematite and siderite may co-exist in iron-formations. Perhaps this may be due to the amount of associated organic matter that was available for bacterial degradation on the basin floor. The net result seems to have been a primary precipitate containing a mixture of ferric and ferrous minerals in a metastable association.

Magnetite is the most abundant iron mineral in metamorphosed iron-formations, and I suggest that the hematite and siderite react to produce magnetite, which appears to be the equilibrium phase at elevated temperatures. In contrast to hematite and siderite, which were involved in the depositional fabric, magnetite typically forms crystal aggregates and veins that tend to obliterate primary features (6). Furthermore, Han (8) showed that much of the magnetite forms as overgrowths on earlier, rhombohedral hematite crystals. It may be appropriate to note here that these diagenetic (?) hematite crystals, which resemble monoclinic selenite crystals, may have been misidentified as pseudomorphs after gypsum (2, 9). If so, this may lead to erroneous interpretations about the oxygen content of the Precambrian atmosphere and oceans.

I suggest that the iron in iron-formations was precipitated as a ferric hydrate product by photosynthetic oxidation of iron in the photic zone. Presumably a variety of organisms were involved in the process, including planktonic iron-stripping bacteria such as Leptothrix and Metallogenium, which precipitated ferric hydrate in their sheaths from ferrous iron in the water. While some of the iron accumulated on the Eosphaera-like structures, most of it evidently formed as minute ferric hydrate particles that settled in the water column. The silica may have been precipitated largely as frustules of silica-secreting organisms, particularly Eosphaera tyleri. Thus, the "sediment rain" consisted of Eosphaera, ferric hydrate, and other organic materials, which accumulated on the basin floor. Incipient layering of iron and silica may have been produced by a relatively constant "rain" of ferric hydrate punctuated by periodic "blooms" of siliceous organisms. In the organic-rich ooze, anaerobic decay and chemoautotrophic bacteria may have flourished, giving off waste CO<sub>2</sub> and ferrous iron. These products reacted to form siderite, which may have been nucleated by the ferric hydrate on the Eosphaera or elsewhere. The notorious lack of sulfide minerals in cherty iron-formations suggests that sulfate was scarce in the basins, and that it did not serve as an oxygen source for organic decay. Continued accumulation of iron on the upper part of the siliceous layer, coupled with diagenetic formation of siderite would produce a marked density contrast between silica and ferruginous "grains". The layering would then be enhanced by currents separating the ferruginous and silica "grains". During periods of higher energy bottom currents, this laminated material might have been broken up to form granule-bearing units in shallower water as discussed by LaBerge (3). Subsequent metamorphism of the metastable siderite-hematite-chert rock would

result in widespread development of magnetite and/or iron-silicates.



Sketch of the proposed model for the biological precipitation of Precambrian iron-formations.

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ARCHEAN SEDIMENTARY STYLES AND EARLY CRUSTAL EVOLUTION; Donald R. Lowe, Department of Geology, Louisiana State University, Baton Rouge, LA 70803

Preserved Archean sedimentary rocks accumulated in at least three major depositional settings represented by sedimentary units (I) in early, pre-3.0 Ga-old greenstone belts, (II) on late Archean cratons formed from the early Archean greenstone belts, and (III) in late Archean, post-3.0 Ga-old greenstone belts.

(I) The principal volcanic sequences of early Archean greenstone belts in the Barberton Mountain Land, South Africa, and the eastern Pilbara Block, Western Australia, contain sedimentary units deposited on low-relief, anorogenic but rapidly subsiding, shallow-water platforms constructed largely of mafic and ultramafic volcanic rocks (1). The primary sediment types included fresh or only slightly reworked pyroclastic debris; orthochemical precipitates including carbonate, evaporites, and silica; and biogenic deposits now represented by black carbonaceous chert, banded chert, and stromatolitic units (1, 2, 3). Terrigenous deposits, such as sandstone and shale derived by weathering and erosion of older rocks, are rare. Algoma-type iron formation, volcanogenic massive sulfide deposits, and turbidites, all of which usually form under deeper-water conditions, are also poorly developed. Detrital modes of clastic units are dominated by volcanic and intraformational sedimentary components and essentially lack coarse alpha-quartz, potash feldspar, and metamorphic and plutonic rock fragments. These units reflect sedimentation on large, shallow-water simatic platforms far removed from sources of sialic detritus.

The upper, sedimentary parts of these early Archean greenstone belt sequences are made up largely of detrital units reflecting orogenesis and deep erosion (4). The debris includes material eroded from both the underlying greenstone belt sequence and quartzose intrusive and metamorphic rocks. Deposition took place in environments ranging from alluvial to deep-sea (4). These units mark the regional transition from simatic platforms to continents.

(II) Following early Archean cratonization, the South African Kaapvaal and Australian Pilbara cratons were subject to deep erosion and, in late Archean time, were the sites of deposition of thick sedimentary and volcanic sequences. These include the Fortescue Group on the Pilbara Block and the Pongola and Witwatersrand Supergroups and succeeding units in South Africa. Although volcanism was widespread during the accumulation of many of these sequences, the sedimentary rocks clearly reflect deposition on relatively stable blocks of continental crust. They directly overlie the eroded plutonic and greenstone belt basement of early Archean age, are much less deformed and metamorphosed than underlying greenstone belt rocks, have not been extensively intruded by granitoid plutonic rocks, and contain large amounts of craton-derived arkosic and quartzitic debris.

(III) Late Archean, post-3.0 Ga greenstone belts in Canada and much of the Yilgarn Block, Western Australia, include sedimentary units in the volcanic part of the sequence that differ significantly from those in the older belts (1). Coarse terrigenous clastic units occur throughout the volcanic section instead of just at the top, as in older belts. These units are made up of conglomerate, sandstone, and shale derived largely by erosion of the greenstone belt sequence itself but contain detritus eroded from penecontemporaneous intrusions and older sialic basement. Deposition was mainly by subaqueous sediment gravity flows, including turbidity currents and debris flows. Shallow-water deposits in the volcanic sections accumulated mainly around high-standing felsic volcanic cones. Carbonaceous cherts, banded cherts, and evaporites are rare, whereas volcanogenic sulfide deposits and Algoma-type

iron formation are widespread. Deposition took place under subaqueous, in large part deep-water, tectonically unstable conditions (1).

As in the older belts, the uppermost clastic units at the top of the greenstone belt sequence reflect orogenesis. They were deposited in an association of environments ranging from alluvial to deep-sea (5).

The sedimentology of these Archean sedimentary systems bears strongly on interpretations of the character and evolution of the Archean crust. (A) The preserved early Archean greenstone belts formed as large, high-standing, anorogenic simatic blocks that were not underlain by or adjacent to significantly older continental crust. They underwent cratonization which age relationships of associated plutonic rocks suggest proceeded more-or-less concurrently with deposition of the greenstone belt sequences (6, 7).

(B) The cratons formed from these early Archean greenstone belts served as sites for the deposition of late Archean volcanic and shallow-water shelf sequences. These deposits are generally similar to cratonic sediments that are abundant in younger sequences and are clearly distinct from greenstone belt sediments.

(C) In contrast to the early Archean belts, late Archean greenstone belts represent largely subaqueous and tectonically active depositional sites (1). Both radiometric dating and included detrital sediments indicate that they formed in close association with significantly older sialic blocks. These belts also underwent cratonization more-or-less concurrently with accumulation of the greenstone belt sequences to form stable continental blocks that hosted the subsequent deposition of early Proterozoic shelf sediments. The co-existence in the late Archean of (a) large, stable cratons in South Africa and the Pilbara, Western Australia, and (b) younger greenstone belts in Canada, the Yilgarn, and elsewhere emphasizes the clear sedimentological and tectonic contrasts between these terranes. These contrasts argue strongly against suggestions that greenstone belts developed upon blocks of continental crust.

These results suggest that the Archean was characterized by at least two diachronous styles of crustal evolution. Early Archean cratons evolved from anorogenic shallow-water simatic platforms, perhaps resembling modern oceanic islands formed over hot spots. These platforms show no evidence of an association with significantly older continental blocks. Late Archean greenstone belts, perhaps analogous to modern magmatic arcs, developed adjacent to but not entirely upon older sialic blocks.

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REGIONAL VARIATION IN THE AMÏTSQ GNEISSES RELATED TO CRUSTAL LEVELS DURING LATE ARCHEAN GRANULITE FACIES METAMORPHISM, SOUTHERN WEST GREENLAND. A.P. NUTMAN<sup>1</sup>, D. BRIDGWATER<sup>2</sup>, V.R. MCGREGOR<sup>3</sup>. 1 Department of Earth Sciences, MUN, St. John's, Nfld., Canada. 2 Geological Museum, Copenhagen, Denmark. 3 Atammik, Greenland.

INTRODUCTION: Regional mapping by the Geological Survey of Greenland has shown that large areas of southern West Greenland preserve middle to late Archean granulite facies assemblages (Chronology, Table 1). From mineralogical and textural evidence further large areas were affected by granulite facies metamorphism but were subsequently retrogressed under amphibolite facies conditions prior to the intrusion of the c. 2550 Ma Qôrqt granite complex (McGregor et al., this volume). In Godthåbsfjord (Fig. 1) however, the rocks appear to have been only metamorphosed under amphibolite facies conditions in the mid and late Archean.

Table 1. Relevant events in the regional chronology.

- 3) Intrusion of post-tectonic Qôrqt granite complex, 2550 Ma
- 7) Deformation, retrogression of granulite facies rocks under amphibolite facies conditions ( A on Fig. 1) and intrusion of granitoid sheets, 2700-2600 Ma
- 6) Granulite facies metamorphism ( [G] on Fig. 1). In south, c. 2800 Ma, in north, c. 3000 Ma.
- 5) Intrusion of the Nûk gneisses. 2900-3050 Ma.
- 4) Deposition of Malene supracrustal rocks.
- 3) Intrusion of the Ameralik dykes.
- 2) Intrusion of the AmÏtsoq gneisses (predominantly 3750-3700 Ma tonalites) accompanied and followed by deformation, metamorphism and granite sheet injection. 3750-3400 Ma.
- 1) Deposition of a supracrustal sequence, represented by the Akilia association and the Isua supracrustal belt. 3800 Ma.

Airborne radiometric surveying (Secher, 1977, & pers. comms.) shows there is considerable areal variation in  $\gamma$ ray (combined K-U-Th-Rb) radioactivity, which persists even after 'stripping' of anomalous concentrations associated with discrete potassic granitoids of various ages, such as the Qôrqt granite complex. This leads to a relatively simple regional pattern for radioactivity: Terranes that have never experienced granulite facies metamorphism are more radioactive than those that have (Fig. 1).

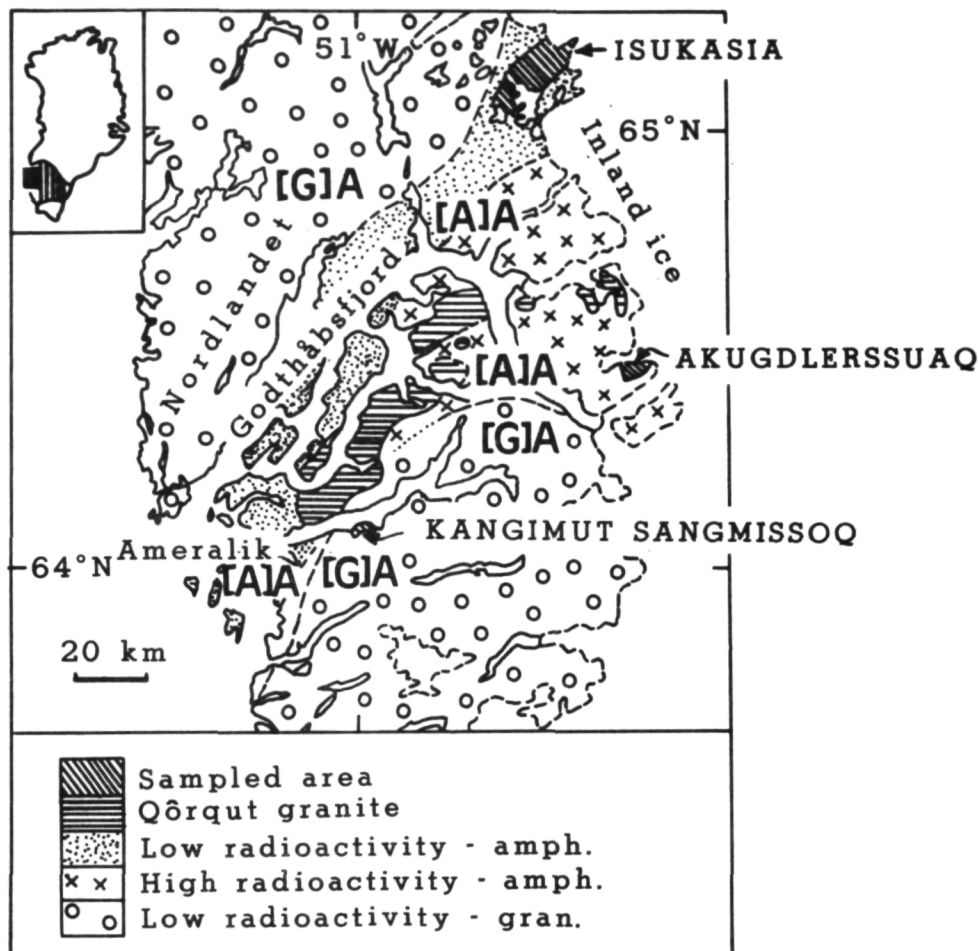


Figure 1. Radioactivity/metamorphic facies zones of study area. [G] - affected by 3000-2800 Ma granulite facies metamorphism [A] - affected by 3000-2800 Ma amphibolite facies metamorphism. A - amphibolite facies metamorphic conditions between 2800-2550 Ma.

The northwestern terrane (Nordlandet) underwent granulite facies metamorphism at c. 3000-2900 Ma, as opposed to at c. 2800 Ma for the granulite rocks in the southeast (e.g. Taylor et al., 1980). This paper compares the southern [G] and the [A] zones (Fig. 1) to see if variation in content of radioactive minerals can be related to the c. 2800 Ma granulite facies event. This is done by examining Amîtsoq grey gneisses, mostly derived from tonalites, from three localities: (1) Kangimut sangmissoq [G], low radioactivity, (2) Akugdlerssuaq [A], high radioactivity and (3) Isukasia [A], moderate to low radioactivity (Fig. 1).

**FIELD RELATIONS:** Late Archean ductile deformation accompanied retrogression of granulite facies rocks ([G] followed by A). Most

obvious are 'straight zones' up to 1 km wide with a steeply dipping LS fabric with amphibolite facies assemblages, and more or less contemporaneous non-cylindrical southerly-plunging folds with wavelengths of up to 15 km. In areas of low deformation granulite facies rocks are patchily retrogressed, with amphibolite facies assemblages mimicking textures developed under granulite facies metamorphism. These textures are obliterated or strongly modified in the zones of strong deformation described above. Granitoid sheets intruded during formation of these structures are between 2700 and 2600 Ma old (McGregor et al., 1983), giving the time of retrogression. The boundaries between the regions of different metamorphic history (Fig. 1) are complicated on a 10 to 20 km scale due to the folding, and in some places the boundary between the southeastern granulite facies terrane and the amphibolite facies terranes of Godthåbsfjord could be a tectonic break. This could explain why well preserved, type Amîtsoq gneisses of outer Ameralik are found juxtaposed with granulite facies rocks slightly further into the fjord (Fig. 1). However, the zonal facies arrangement appears valid on the regional scale (?00km).

It is likely that 2700-2600 Ma deformation juxtaposed regions that were at different crustal levels during the c. 2800 Ma granulite facies event, so that 2800 Ma granulite facies rocks outcropping in the south were probably overlain by amphibolite facies terranes equivalent to those found in Godthåbsfjord. Rb-Sr data on retrogressed granulites to the north of Godthåbsfjord (Garde et al., in press) shows that c. 3000 Ma gneisses there were 'reset' under amphibolite facies conditions at c. 2850 Ma. This suggests that during the c. 2800 Ma granulite facies event in the south, that c. 3000 Ma granulite facies terrane to the north was not at great depth, and formed a metastable granulite facies block in the middle-crustal level amphibolite facies terranes.

The character of the quartzofeldspathic components of the three areas sampled in this study is outlined below.

Kangimut sangmissoq: The dominant lithology here is buff-coloured, medium to coarse-grained, somewhat inhomogeneous to nebulitic tonalitic gneisses that contain remnants of plagioclase-phyric amphibolite dykes that lithologically and geochemically resemble poorly-preserved Ameralik dykes from the type area, 10 km to the west. The gneisses contain granulite facies assemblages but show widespread retrogression under amphibolite facies conditions. The Kangimut sangmissoq rocks are part of a large raft intruded first by massive tonalites that resemble main phases of the Nûk gneisses s.s., emplaced between 3050 and 2900 Ma (Baadsgaard & McGregor, 1981), and then by 2700-2600 Ma (post granulite facies) granitoid sheets (Roberts, 1979; McGregor et al., 1983). The Kanigmut sangmissoq gneisses are interpreted as containing an appreciable component of Amîtsoq gneisses (McGregor et al., this volume). Isotopic data on these rocks, when considered in isolation, do not conclusively show that these rocks are early Archean (S. Moorbath, P. Taylor & H. Baadsgaard pers. comms. & Collerson et al., this volume).

Akugdlerssuaq: The gneiss complex is dominated by amphibolite facies schlieric and nebulitic gneisses with disrupted amphibolite dykes (with discordances only rarely preserved), and containing enclaves of banded amphibolite and banded iron formation (Akilia association). These are cut by coarse-grained granite and pegmatite sheets, that in places can be hard to distinguish from, and grade into, in situ neosome. The complex was then



cut by sharp-margined sheets of tonalitic to granitic composition, and was further deformed under amphibolite facies conditions (Nutman, 1982). The gneisses are interpreted as containing an Amîtsoq component, that was affected by two episodes of late Archean migmatization. Rb-Sr and Pb-Pb isotopic studies from this and adjacent areas show that the isotopic systematics of Amîtsoq gneisses was strongly disturbed in the late Archean and that the grey sheets are 2700-2600 Ma old (Robertson, 1983; S. Robertson & M. Brewer, pers. comms; Bridgwater, Nutman & Larsen, unpublished data). Isukasia: The gneisses consist of 3750-3700 Ma tonalites veined by c. 3600 Ma granite sheets and comparatively rare c. 3400 Ma pegmatite dykes (Nutman et al., 1983; Baadsgaard et al., in prep.). In the late Archean there was heterogeneous deformation, but no significant migmatization. The Amîtsoq gneisses of this area widely preserve their early Archean characters, whilst in the other areas discussed above late Archean tectonometamorphic overprinting and migmatization have obliterated their early Archean characters.

GEOCHEMISTRY: This study considers grey gneisses that have undergone different metamorphic histories. From field work the samples are identified as derived from >3600 Ma tonalitic and banded Amîtsoq grey gneisses. However from the point of view of element migration discussed here, this age identification is unimportant since similar features are developed in polymetamorphic suites of Nûk gneisses at localities adjacent to those chosen for this study.

There is marked variation seen in the composition of these rocks in areas of different metamorphic history (Table 2). For example Akugdlerssuaq, where metamorphic grade was not above amphibolite facies and which forms part of the belt of high radioactivity (Fig. 1), there is a gain of LREE, Th, Rb, Pb, and K relative to both rocks from the low radioactivity, granulite facies terrane (e.g., Kangimut sangmissoq) and the well preserved, low radioactivity, amphibolite facies terrane to the north (e.g. Isukasia).

Table 2. Significant regional variation in composition of Amîtsoq grey gneisses (expressed as average abundance - more than 15 samples per group).

	K <sub>2</sub> O	Rb	Pb	Th	Ce
Isukasia [A], moderate radioactivity	1.61	85	17	4	37
Akugdlerssuaq [A], high radioactivity	2.36	104	22	11	141
Kangimut sangmissoq [G] low radioactivity	0.57	9	8	1	29

There seems to be a good correspondence between metamorphic history and regional variation of radioactivity and geochemistry. It is suggested that the amphibolite facies, high radioactivity zone represented by Akugdlerssuaq could be an enriched zone, containing LIL elements expelled from underlying granulite facies terrane, represented here by Kangimut sangmissoq. The amphibolite facies, low radioactivity rocks of Isukasia are interpreted as a part of a crustal level above the enriched zone, not significantly metasomatised and intruded by granitoids during the granulite facies metamorphism at depth. Accepting this explanation implies redistribution

of LIL elements on the scale of several kilometres during granulite facies metamorphism. In a heterogeneous, polyphase gneiss complex, this must have involved isotopic mixing between lithologies of different ages and origins, leading to modification of the isotopic signatures of the units (McGregor et al. & Collerson et al., this volume). It is apparent that enrichment of LIL elements in the gneisses from the enriched zone (Akugdlerssuaq) could in part be introduced via the injected granitic and pegmatitic sheets, that form at the most 10% of the gneisses complex at Akugdlerssuaq, and at other comparable localities such as Nordafar (see Collerson et al., this volume). However, the likely reason for concentration of these sheets is their derivation as either melts or hydrous fluids from the area undergoing granulite facies metamorphism (Bridgwater et al., in press; Schiøtte et al., in press).

DISCUSSION: The regional variation of Amîtsoq gneiss compositions combined with structural interpretations suggest that the c. 2800 Ma crust of the region was stratified, with granulite facies terrane at depth, (e.g., Kangimut sangmissoq) overlain by enriched amphibolite facies containing LIL elements expelled from the granulite facies terranes (e.g., Akugdlerssuaq) and capped by non-enriched, relatively undisturbed amphibolite facies terrane (e.g., Isukasia). Such stratification has also been discussed for other areas (e.g. Newton et al., 1981; Condie et al., 1982; Schiøtte et al., in press). Development of such a layer cake structure with a zone rich in LIL elements imposes important controls on subsequent anatexis and granitoid generation.

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# METAMORPHISM AND PLUTONISM IN THE QUETICO BELT, SUPERIOR PROVINCE, N.W. ONTARIO

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Reconnaissance study of 350 km of strike length of the 1200-km-long Quetico belt reveals regional patterns of metamorphism and plutonism. Located between the Wabigoon and Wawa greenstone-granite belts, the Quetico belt consists of a marginal metasedimentary schist unit and an interior complex of metasedimentary schist and gneiss and plutonic rocks. Metamorphic grade in marginal pelitic schists varies from a chlorite-muscovite zone at the outer margin to a garnet-sillimanite zone toward the interior. Common assemblages of garnet-andalusite throughout the marginal unit and in the interior in the Lac La Croix area indicate low-pressure metamorphism (bathozone 2). Assemblages of staurolite-sillimanite and rare kyanite some 60-150 km east of Lac La Croix suggest bathozone 3 conditions. Mineral assemblages in peraluminous granitoid leucosome dykes and plutons also vary regionally along strike. Sillimanite, in association with garnet and muscovite, is common in the west; cordierite is present only to the east. Leucosome in migmatites is mainly intrusive in the west and locally derived in the east. These features together suggest a deepening level of erosion from west to east.

Two large plutonic complexes characterize the interior of the western Quetico belt: the Vermilion complex of Minnesota and the Quetico Park complex (1) of Ontario. The Vermilion complex consists mainly of biotite granite and leucogranite with metasedimentary schist inclusions. A zonation in plutonic rock types characterizes the Quetico Park complex across its 20-50 km width. Peraluminous white granite of the Sturgeon Lake batholith (2) occurs in the centre of the complex and is flanked by older, small (<10-km-wide) plutons of pink biotite + magnetite leucogranite, rarely with inclusions of monzonite-diorite-hornblendite. Small (> 5 km) plugs of diorite-monzonite cut marginal metasedimentary schists.

The two granite types of the Quetico Park complex have distinctive mineralogical, textural and chemical characteristics. Biotite leucogranites are generally homogeneous, massive medium-grained rocks with less than 5% biotite and some magnetite. Granites of the Sturgeon Lake batholith are coarse-grained to pegmatitic, have numerous metasedimentary inclusions and contain some combinations of garnet, muscovite, sillimanite, cordierite, biotite, apatite, tourmaline and rare fluorite in addition to quartz and alkali feldspar. Ferromagnesian minerals have high Fe/Fe+Mg ratios and garnet is spessartine-rich. Chemically, the Sturgeon Lake rocks are higher in SiO<sub>2</sub> than biotite leucogranites, and lower in TiO<sub>2</sub>, Fe<sub>2</sub>O<sub>3</sub>, FeO, Fe<sub>2</sub>O<sub>3</sub>/FeO, CaO, Na<sub>2</sub>O, Na<sub>2</sub>O/K<sub>2</sub>O, Rb, Sr and REE. Biotite leucogranite has a fractionated REE pattern with a negative Eu anomaly (3).

Zircons in both granite types are complex, with cores and overgrowths and resorbed appearance. Texturally-simple monazite is being used in U-Pb geochronology.

U-Pb zircon geochronology places constraints on the timing of development of the Quetico belt. In the Wabigoon metavolcanic belt to the north, volcanism and early plutonism occurred at 2750-2702 Ma and late plutonism at 2695-2680 Ma (4).

The Wawa-Shebandowan metavolcanic belt was active at the same time, with volcanism in the interval 2749-2696 Ma (5) and late plutonism at 2690-2675 (6). Sediments were deposited in the Quetico basin before intrusion of the Poohbah Lake complex at ~2700 Ma (7) and were probably derived from adjacent volcanic highlands.

A composite section through the belt shows steeply inward-dipping margins and tadpole-shaped plutons derived from a metasedimentary source in the centre and tonalitic rocks of the greenstone-granite terranes towards the margins. A back-arc or inter-arc basin environment is postulated to account for early development of an elongate sedimentary trough characterized by high heat flow which led to later deep crustal melting and magma rise to high structural level. Underplating by mafic magmas possibly contributed to heat transfer from the mantle to the lower crust.

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EARLY ARCHEAN TONALITE GNEISS IN THE UPPER PENINSULA OF MICHIGAN; Zell E. Peterman, R. E. Zartman, and P. K. Sims, U.S. Geological Survey, MS 963 Box 26046 DFC, Denver, CO 80225

**REGIONAL SETTING.**--Early Archean<sup>1</sup> gneisses are exposed in the core of a structural dome near Watersmeet in the upper peninsula of Michigan (Fig. 1). These gneisses are part of an extensive gneiss terrane in the Lake Superior region [1] that lies immediately south of a Late Archean greenstone-granite terrane (the Wawa Volcanic Belt of Canadian usage). Other occurrences of such old rocks in this region are Early Archean gneisses in southeastern Minnesota [2] and Middle Archean gneisses [3] in central Wisconsin. The two terranes are joined along a fundamental structural feature called the Great Lakes tectonic zone [4] that extends from west-central Minnesota to and possibly beyond the Grenville Front in Canada. This feature exerted a sustained influence on the structural evolution of the region through the Early Proterozoic with the gneiss terrane generally exhibiting greater mobility than the greenstone-granite terrane during the Penokean orogeny at 1.8 to 1.9 Ga.

**GEOLOGY.**--The gneiss dome near Watersmeet (Fig. 2) contains a diversity of rock types and tectonic overprints that record a remarkably long interval spanning nearly two billion years of earth history. Isotopic dating [5,6] and field studies [7] have elucidated much of this protracted geologic record. The oldest unit is a tonalitic augen gneiss which is overlain by a succession of well-layered biotite gneiss and schist. Both of these units are Early Archean. These Early Archean gneisses were overlapped by Late Archean volcanic and sedimentary rocks that formed during the development of the volcanic belt immediately to the north. The Late Archean units are amphibolite and interlayered biotite and biotite-hornblende gneiss. All of the gneisses are cut by leucogranite dikes that were emplaced after the gneisses were folded. Collectively, the Early and Late Archean rocks formed the basement on which a thick succession of sedimentary and volcanic rocks of the Early Proterozoic Marquette Range Supergroup were deposited. Reactivation of the Archean basement during the Penokean orogeny led to the development of gneiss domes that rose diapirically to penetrate the overlying supracrustal rocks.

**GEOCHRONOLOGY.**--The isotopic systems in the Archean rocks were strongly disturbed during the episode of ductile deformation that resulted in the formation of the gneiss domes. Rb-Sr whole-rock systems were open over a scale of several meters suggesting the presence of fluids. Mineral (Pl-Mi-Bi) data yield good isochrons of about 1,750 Ma, and metamorphically reconstituted zircon from biotite gneiss in a ductile-brittle shear zone gives concordant U-Pb ages of 1,757 Ma [5,6].

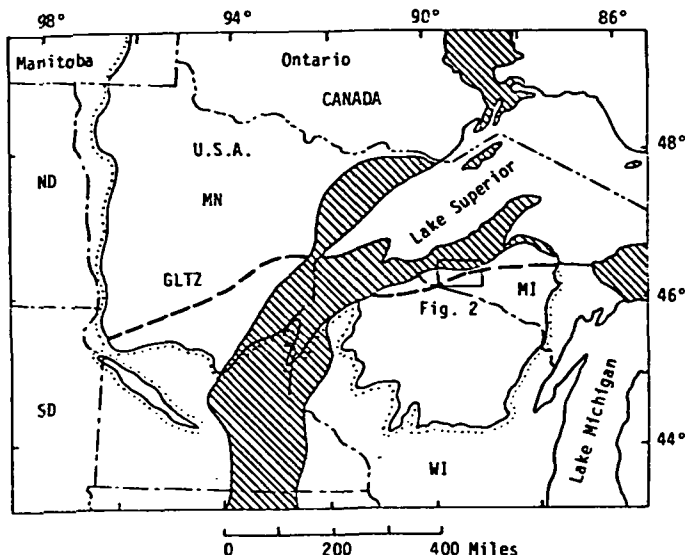
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<sup>1</sup> DNAG Precambrian classification [8]. Intervals are: Late Proterozoic, 570-900 Ma; Middle Proterozoic, 900-1600 Ma; Early Proterozoic, 1600-2500 Ma; Late Archean, 2500-3000 Ma; Middle Archean, 3000-3400 Ma; and Early Archean, 3400-3800(?).

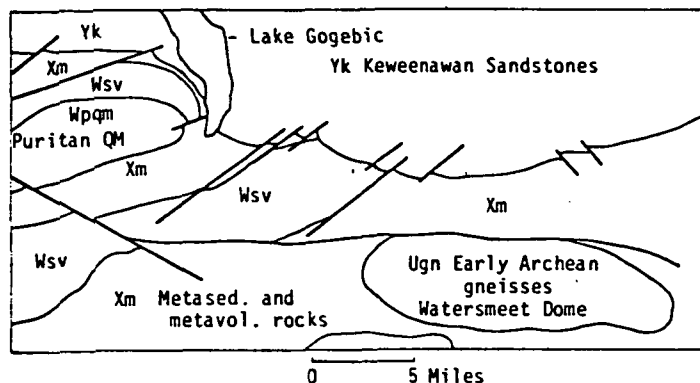
U-Pb zircon systematics [5,6] for Archean rocks in the Watersmeet dome are shown in Figure 3. The array for the Early Archean gneisses is comprised of data for size and magnetic fractions of zircon from two samples of augen gneiss and one sample of biotite gneiss. Zircons from all three samples are very similar in shape, crystal face development, zoning, and color. This array, with some excessive scatter, defines a chord with intercepts at  $3560 \pm 40$  Ma and  $1250 \pm 90$  Ma. Three fractions of zircon from a biotite gneiss in the Late Archean amphibolite sequence give an upper intercept of 2640 Ma but a much younger lower intercept of about 630 Ma. Size fractions of zircon from a leucogranite dike suggest an emplacement age of about 2590 Ma. The concordant zircon from biotite gneiss in a zone of very high strain in the dome is shown at 1,760 Ma.

The lower intercept age of 1250 Ma for the Early Archean chord doesn't correspond well to any known event in the region, Keweenaw igneous activity and rifting at about 1100 Ma being the closest in time. This anomaly and the much younger lower intercepts shown by the Late Archean zircons has led us to suggest that the disposition of points for the Early Archean zircons is the result of multiple episodes of lead loss in a fairly systematic fashion [6]. Episodic loss of lead at 2.7, 1.8, and 0.5 Ga could produce a trajectory on a concordia diagram which would be nearly linear over the interval represented by actual data points. Subsequent ion microprobe analyses by Williams and others [9] of one of the least discordant zircon fractions (Fig. 3) has shown additional complexities in the discordance pattern. They found domains within grains that yielded nearly concordant results and extended the age to 3650 Ma. They also found overgrowths that had formed at 2600 Ma when the Early Archean gneisses and overlying Late Archean supracrustals were deformed, metamorphosed, and intruded by granite. In this particular sample, no evidence was found for the Early Proterozoic event suggesting that its effect on the U-Pb zircon systems was restricted to zones of exceptionally high strain such as that which produced the concordant 1760-Ma zircon.

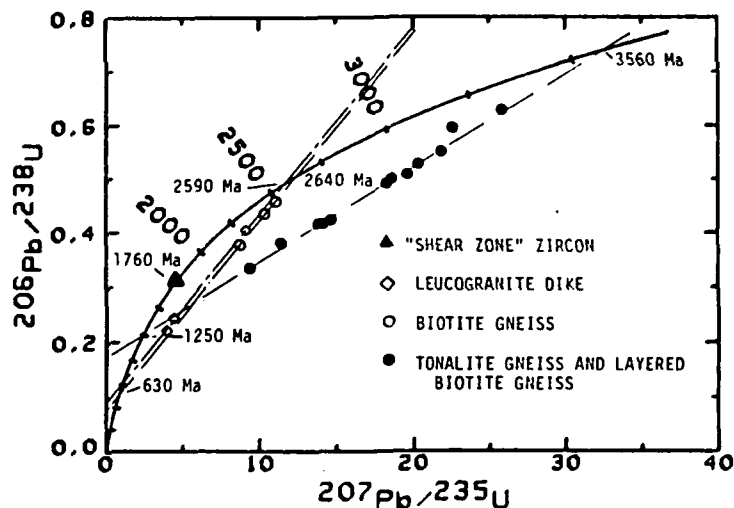
Archean rocks northwest of the dome are part of the Late Archean greenstone-granite terrane (Fig. 2). Zircons from a biotite gneiss in a bimodal gneiss-amphibolite sequence presumed to be interlayered mafic and felsic volcanic rocks are dated at 2750 Ma, somewhat older than the similar 2640-Ma sequence infolded with the Early Archean gneisses in the dome. The Puritan Quartz Monzonite, the principal granite in the greenstone-granite terrane in this area is dated at 2650 Ma by Rb-Sr [10]. Whole-rock samples of Early Proterozoic metagraywackes immediately north of the dome give a Rb-Sr isochron age of  $1820 \pm 50$  Ma. This is a metamorphic age representing resetting attendant with dewatering and recrystallization of the matrix. It is consistent with whole rock and mineral isochrons within the dome that reflect resetting during deformation related to the doming.



**Figure 1.**--Index map showing location of Fig. 2. Diagonally ruled area represents 1100 Ma Keweenaw igneous and sedimentary rocks of the midcont. rift system. The line-dot pattern shows the limit of Paleozoic strata. GLTZ is the Great Lakes Tectonic Zone that separates remnants of Early to Middle Archean gneisses on the south from the Late Archean greenstone terrane on the north.



**Figure 2.**--Simplified geology in the vicinity of the Watersmeet dome. Outcrops of Early Archean gneisses are along northern edge of dome. Wsv refers to Late Archean metased. and metavol. rocks. Other units are defined on the map. The GLTZ lies between the Watersmeet dome and the Puritan Quartz Monzonite.



**Figure 3.**--Concordia diagram for zircons from Early and Late Archean rocks in the Watersmeet dome. Differences in lower intercepts suggest that the Early Archean array is the result of multiple episodes of lead loss and that 3560 Ma is probably a minimum age.



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## PETROGENESIS OF CALCIC PLAGIOCLASE MEGACRYSTS IN ARCHEAN ROCKS;

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Anorthositic complexes with large (up to 20 cm across) equidimensional plagioclase grains of highly calcic composition (An<sub>80-90</sub>) occur in nearly all Archean cratons. Similar plagioclase occurs as megacrysts in many Archean sills, dikes, and volcanic flows. In the Canadian Shield these units occur throughout the Archean portions of the entire shield and are particularly common as dikes over an area of a few 100,000 km<sup>2</sup> in Ontario and Manitoba during a period of at least 100 my (between 2.6 and 2.8 by) in many different rock types and metamorphic grades. In Ontario megacrysts occur in the Matachewan dikes (1) which intrude tonalitic gneisses, greenstones, and granites. In Manitoba low grade greenstone belts that contain anorthosites can be traced into equivalent units in high grade granulite terrain that contains similar anorthosite (2). In addition, large inclusions of anorthosites of potentially Archean age occur in younger Precambrian intrusions of northeastern Minnesota and central Wisconsin (3). In summary, these occurrences indicate a common, widespread, long-term igneous process in the Archean at crustal to sub-crustal levels.

Because the anorthositic complexes are clearly crystal segregations and the megacrysts in the sills, dikes, and flows are generally not in equilibrium with their matrices, the nature of the melt from which the calcic plagioclase formed has remained elusive. Attempts to determine the melt composition through REE distribution coefficients are hindered by the fact that REE concentrations, especially the heavy REE, are quite low in plagioclase and may be significantly enriched (see Fig. 1) by alteration, contamination, and recrystallization, all of which are common in Archean anorthosites. For the very few megacrysts that appear relatively fresh and from attempts to subtract contaminants or alteration from suites of plagioclase, the most recent REE distribution coefficients for plagioclase-basalt equilibrium indicate a parent melt with a somewhat light depleted REE pattern at about 10-20X chondrites, similar to the range of REE patterns of the less fractionated tholeiites in Archean greenstone belts. In essentially all intrusive anorthositic complexes the original mafic material has been completely, or almost completely, recrystallized generally to amphiboles or mixtures of amphibole and chlorite thereby eliminating any opportunity to use distribution coefficients with any mineral other than plagioclase.

The plagioclase generally occurs in three modes: as inclusions in mafic intrusions at various stages of fractionation (4), as crystal segregations in anorthosite complexes (5), or as megacrysts in fractionated sills, dikes, and flows (6). Most occurrences suggest that the plagioclase was formed elsewhere before being transported to its present location. Generally, the large plagioclase grains are quite uniform in composition at An<sub>80</sub> to An<sub>85</sub>, although individual grains may differ in a single thin section. However, in many dikes, sills, and flows there are many grains with very thin rims of a much lower An content approaching that of the matrix plagioclase (see Table 1). This relationship holds regardless of the grain size of the matrix whether it be very fine-grained basalt or medium-grained gabbro. In the Bird River area of SE Manitoba An<sub>85</sub> megacrysts occur in matrices that are coarse-grained and contain homogeneous plagioclase that may be An<sub>35</sub> in one unit and An<sub>85</sub> in another. In a few of the occurrences, however, the bulk of the large plagioclase grains may be homogeneous at An<sub>80</sub> to An<sub>85</sub> but their outer rims are complexly zoned. In the Bird River area there are discrete steps in the zoning

of these outer rims with the steps being at An 73-75, An55-57, An38-40, and An23-25. The number and sequence of steps varies from grain to grain, even between adjacent grains, thereby suggesting a complex set of infusions of interstitial melt or significant stepwise changes in fugacities of volatiles.

The evidence seems to be quite clear that occurrences of these types of calcic plagioclases require: 1) ponding of a relatively undifferentiated Archean tholeiitic melt at some depth, 2) isothermal crystallization of large, equidimensional homogeneous plagioclase crystals, 3) separation of the plagioclase crystals from any other crystalline phases, 4) further fractionation of melt, 5) transport of various combinations of individual plagioclase crystals and clusters of crystals by variously fractionated melts, and 6) emplacement as various types of igneous intrusions or flows. It is quite possible that intrusions of this type could deposit their plagioclase crystals as anorthosite while most of the melt continues to shallower or surface levels or, alternatively, the melt could crystallize as gabbros amongst the previously formed plagioclase to form an anorthositic complex.

The major remaining question is the location of plagioclase crystal formation when the melt is first ponded. The most likely location for ponding is at a density barrier that could trap rising melts in a stratified density sequence. Such possible density barriers could occur at the crust-mantle boundary or at changes in metamorphic mineral assemblages in the lower crust. As the ponded melt cools and crystallizes, the high density mafic phases would sink to become parts of the uppermost mantle or lower crust and the lower density plagioclase, being less dense than essentially all mafic melts at these depths, would float or remain in suspension in the melt. As the melt density decreased during differentiation, or fractures developed from tensional stresses during doming, rifting, or other tectonic processes, the melts would rise with entrained plagioclase as crystals, clots, or anorthosite fragments to form flows, sills, or dikes containing megacrysts, complexes of anorthositic rocks, or inclusions of anorthosite.

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## CALCIC PLAGIOCLASE MEGACRYSTS IN ARCHEAN ROCKS

Phinney, W.C. et al.

Table 1

## Matachewan Dikes: Plag. Compositions

LOCATION	CRYSTS			MATRIX LATHS	
	main cryst	inner rim	outer rim	core	rim
Sta 8	An79-81	An56	An42-49	An61-64	An47
9-11	80-82	66-69	54	65-69	54
10	75-78	61-62	54	58-61	45-50
16	81-84		62-67	68-70	52-53
16	82-84		64-65	64-66	46-53
16	83-85		72-76	71-72	66-69
18	Too Altered			50-54	33
34	81-83			No laths	
35	81-83		78-80	61-63	51-54

## UTIK LAKE

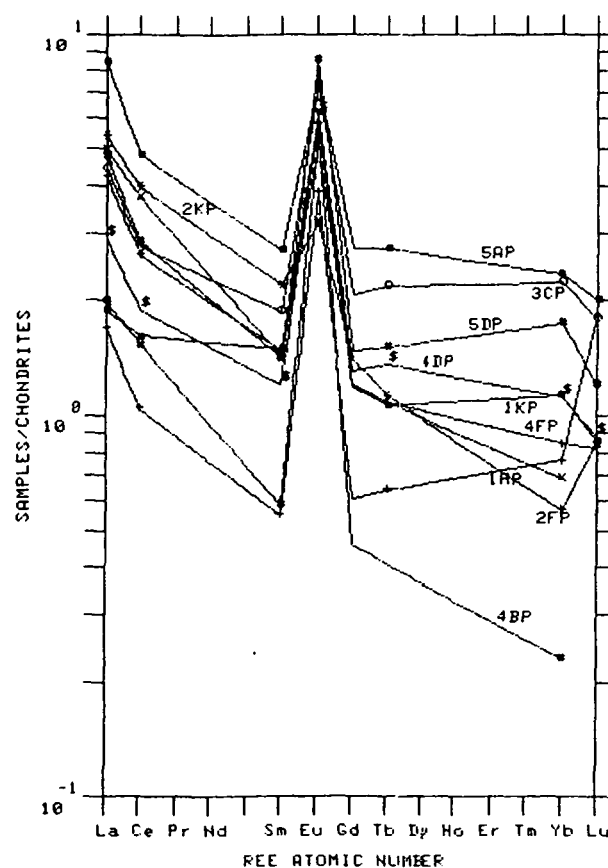


Figure 1. REE patterns for plagioclase megacrysts from flows and sills at Utik Lake, Manitoba.

INTRUSIONS OF MIXED ORIGIN MIGMATISING EARLY ARCHAEOAN CRUST IN NORTHERN LABRADOR, CANADA. L. Schiøtte and D. Bridgwater, Geologisk Museum, Østervoldgade 5-7, 1350 København K., Denmark.

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In the Saglek-Hebron area of northern Labrador, Canada, old-Archaeoan (23.6 Ga) gneisses and supracrustals are migmatized by late-Archaeoan granites and trondhjemites.

A simplified chronological scheme of the geological evolution in the area compared to Godthaabsfjord, West Greenland is shown in Table 1. In the early Archaeoan the evolution of the Labradorian Uivak continent has much in common with the evolution of the Greenlandic Amitsoq continent. In the later Archaeoan, however, remelting and reworking of the already existing continent plays a more important role in Labrador, than is described from the type area of the Amitsoq gneisses between Godthaabsfjord and Ameralik (1). Conversely the equivalent of the ca. 3000 Ma Nûk gneiss (s.s.) which is dominated by rocks formed from protoliths with a short crustal history, has only

Table 1.

Simplified geological table of events for the Archaeoan of the Saglek-Hebron area and outer Godthaabsfjord.

	<u>Saglek-Hebron:</u>	<u>Godthaabsfjord:</u>
~3600 Ma	Uivak continent established (incl. rafts of Nulliak supracrustals).	Amitsoq continent established (incl. rafts of Isua/Akilia supracrustals).
	Saglek dyke swarm.	Ameralik dyke swarm.
	Deposition of Upernavik supracrustals.	Deposition of Malene supracrustals.
~3000 Ma	Intrusion of Lister gneiss, restricted extent.	Intrusion of anorthosite followed by wide spread Nûk gneisses.
	Tectonic intercalation of gneisses and Upernavik supracrustals.	Tectonic intercalation of gneisses, anorthosites and Malene supracrustals.
~2800 Ma	Wide spread granulite facies metamorphism, partial melting of continent. Granitic-trondhjemitic migmatizing sheets.	Granulite facies metamorphism.
	Emplacement of discrete pink-grey granitic sheets.	Emplacement of Qârusuk dykes. (Wide spread granite sheeting in inner Godthaabsfjord).
~2500 Ma	Formation of post-tectonic K-feldspar rich granite.	Formation of post-tectonic Qôrquut granite.
	Data from (2-5)	

got a very restricted extent.

Late-Archaeon sheets which migmatise the old-Archaeon rocks, are intruded during the waning stages of high-grade metamorphism. Different crustal levels of the late-Archaeon migmatite complex are seen at the present level of erosion, due to post-Archaeon faulting of the Saglek-Hebron area. In the deepest crustal levels the migmatising sheets crystallised in granulite facies. At intermediate levels the granulite facies conditions had ceased at the time of intrusion, and migmatisation is locally related to retrogression. At the highest crustal levels represented, the migmatising sheets cut gneisses which did not reach granulite facies during the late-Archaeon.

The sheets are leucocratic with very restricted amounts of mafic minerals (opx and gar in granulite facies, biot and occasional gar in amphibolite facies).  $K_2O/Na_2O$  ratios show a large spread, even within one intrusion. Absolute contents of REE are generally low (fig. 1), with prominent positive Eu-anomalies. LREE are in most cases highly enriched relative to HREE, that is  $(Ce/Yb)_N$  50-250. A garnet-bearing K-feldspar rich pegmatite (fig. 1), however, shows a concave REE-pattern.

These REE-patterns are difficult to explain in terms of simple magma differentiation from trondhjemite to granite (which would mainly be a matter of plagioclase fractionation), and we interpret the variable  $K_2O/Na_2O$  ratios as due to alkali exchange with fluids within the sheets and the surrounding gneisses. We suggest that REE and other trace elements usually considered immobile were involved in this interchange. The main factor controlling REE distribution in these fluid-rich environments is thought to be the stability of the main REE bearing phases (allanite, zircon, apatite and garnet). Eu could always easily be accommodated by the very feldspathic rock itself whilst allanite grown in the Uivak gneiss adjacent to migmatising sheets, suggests LREE enrichment by interchange across the contact. The concave REE-pattern displayed by one sample in fig. 1 is accounted for by HREE incorporation in garnet.

Provisional Sm-Nd isotopic measurements of the migmatising sheets show negative, though numerically small  $\epsilon_{Nd}$  (2800 Ma)-values, ranging from -2 to -4. Since  $\epsilon_{Nd}$  (2800 Ma)-values for Uivak gneisses and Nulliak supracrustals are strongly negative (-5 to -10), this suggests a mixed origin for the migmatising sheets with both crustal and mantle like components. If REE exchange with the surrounding rocks took place, the Uivak gneisses (and Nulliak supracrustals) would have been contaminated with an abnormally radiogenic Nd in the late Archaean, in which case previously reported (6) positive  $\epsilon_{Nd}$  (3665 Ma)-values of Uivak gneisses could be an artifact and not necessarily indicative of derivation from a depleted mantle source.

Pb-Pb results also indicate that upper crustal levels were contaminated with Pb of abnormal isotopic composition during the late-Archaean migmatisation. In fig. 2 granulite and amphibolite facies Uivak gneisses reveal a difference in Pb-radiogenicity which is not explicable in terms of U-loss from granulite grade areas at 2800 Ma. If U-loss and partial isotopic homogenisation were the only disturbing factors, the only systematic variation between amphibolite and granulite facies rocks would fall along a line with 2800 Ma slope. From fig. 2 it can be seen that amphibolite facies rocks have radiogenic Pb with an abnormally high  $^{207}Pb/^{206}Pb$ -ratio (that is radiogenic Pb developed before 2800 Ma). If Uivak gneisses do not have different histories between the early Archaean and the late-Archaean high-grade metamorphism on different sides of the facies boundaries, the easiest explanation is that amphibolite facies gneisses were contaminated with radiogenic Pb at 2800 Ma.

The granitic-trondhjemitic migmatising sheets have suitable Pb-compositions for being the contaminating agents. (Direct evidence of Pb mobility is seen in local galena mineralisations of probable late-Archaean age in the area).

[The main conclusion is that granitic-trondhjemitic sheets and their related fluid phases acted as vehicles for element

transport from one crustal level to another. This caused isotopic anomalies in the Pb-Pb and possibly also the Sm-Nd systems. Both isotopic systems indicate a mixed origin for the migmatizing sheets, with crustal as well as mantle components. From their general geochemistry and mineralogy the most probable origin of the migmatizing sheets was melting of sialic crust. The mantle component may either have been introduced by fluid metasomatism directly from the mantle, or alternatively by derivation from adjacent Upernavik supracrustals if these had a short crustal history.

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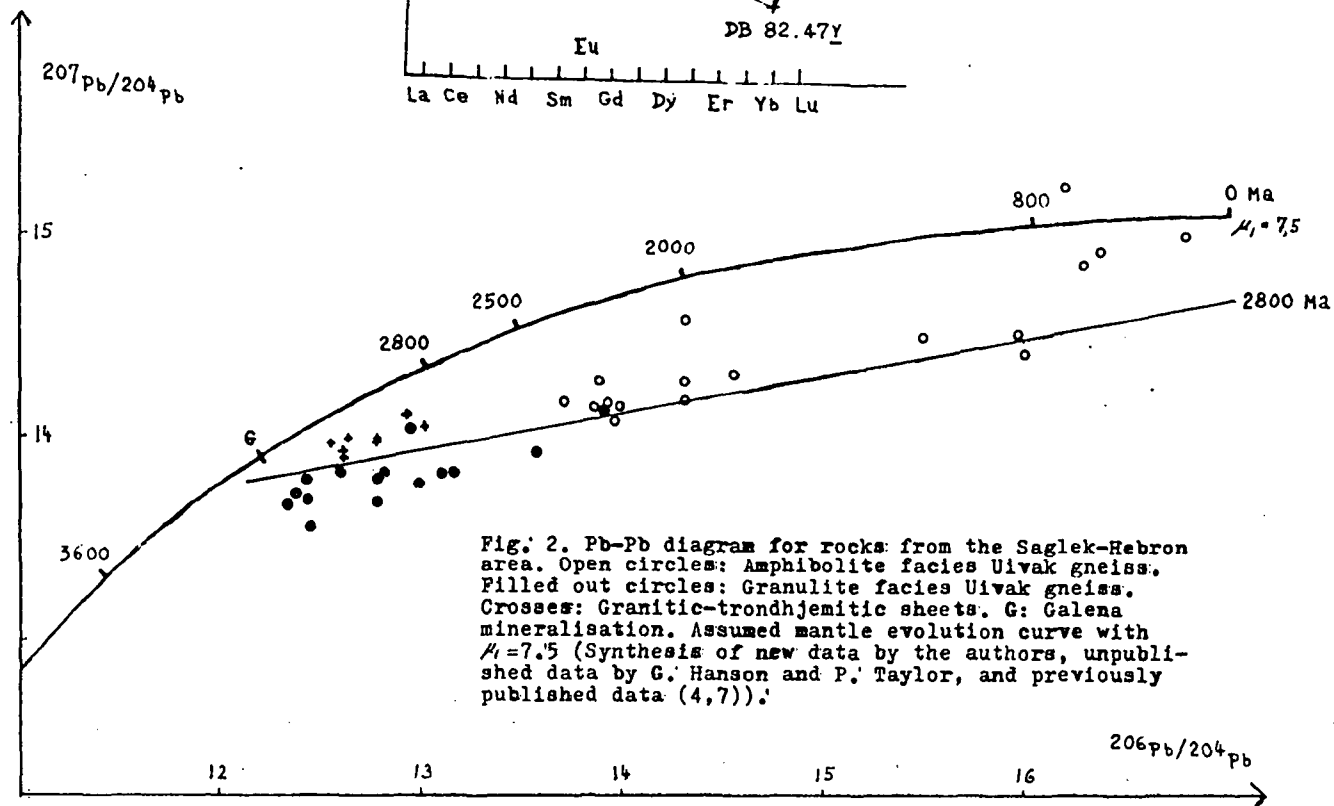
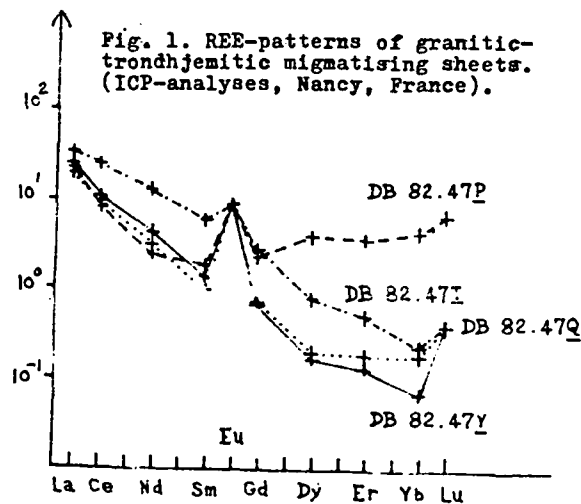
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SOME EXAMPLES OF DEEP STRUCTURE OF THE ARCHEAN FROM GEOPHYSICS;  
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[The development of Archean crust remains as one of the significant problems in earth science, and a major unknown concerning Archean terrains is the nature of the deep crust. The character of crust beneath granulite terrains is especially fascinating because granulites are generally interpreted to represent a deep crustal section.]

Some of the oldest Archean crust in North America is found in the Precambrian of Minnesota, which has dates of 3.6-3.8 b.y. (1). Here the ancient Minnesota Valley gneiss terrain is bounded on the north by the Great Lakes tectonic zone (2) and a series of late Archean greenstone belts. The Great Lakes tectonic zone was presumed to be a steeply dipping Archean border but COCORP crustal reflection data (3,4) shows a gently dipping reflection beneath the zone. Because some of the best crustal reflectors may be fault zones along which mylonites have formed within the ductile regime (5,6), the reflection could be caused by a mylonitic thrust fault. It could equally well be interpreted as a mylonitic listric normal fault, especially since younger rocks lie on older across the fault. However, the indication of a major recumbent fold above the fault reflection (4) suggests that this event is coming from a thrust fault; mylonitization along the fault zone is the postulated cause of the strong, multicyclic-reflection (6). [Magnetic data from this area can be best modeled with a magnetized wedge of older Archean rocks (granulitic gneisses) underlying the younger Archean greenstone terrain (Fig. 1). The dip of the boundary based on magnetic modeling is the same as the dip of the postulated thrust-fault reflection. Thus several lines of evidence indicate that the younger Archean greenstone belt terrain is thrust above the ancient Minnesota Valley gneiss terrain, presumably as the greenstone belt was accreted to the gneiss terrain, so that the dipping reflection represents a suture zone.] This dipping reflection, however, with a thickness of about 1-2 km, seems remarkably simple to represent an Archean suture. Its apparent simplicity may just be a function of resolution in the seismic survey and the postulated suture may be more geologically extensive and broader.

Other dipping events beneath the greenstone terrain may also be reflections from thrusts. Thus by at least late Archean time, a horizontal tectonic regime was dominant. This may reflect the operation of plate-tectonics mechanisms, and if greenstone belts are formed around island arcs, then their presence is more evidence for early plate tectonics.

[Seismic data from underneath the granulite-facies Minnesota gneiss terrain shows abundant reflections between 3 and 6 s, or about 9 to 20 km. These are arcuate or dipping multicyclic events indicative of layering.] Flat events continue to 10 s or more than 30 km. The gneisses consist of granodioritic to tonalitic gneisses with mafic layers or schlieren and garnets (7). Foliation in the gneiss generally dips moderately. Although the layered sequences underlying the gneiss could be mylonites their arcuate geometry and general geologic setting suggest that these events are caused

by layered gneisses that could represent a supracrustal sequence (although with transposed layering). This indicates that no mafic residuum from anatexis closely underlies the gneiss unless it is highly heterogeneous. The significance of layering may rather be to indicate a large-scale migmatite terrain. This reflection data furnishes important information concerning what underlies a granulite terrain. The rocks appear to be a heterogeneous, layered, deformed sequence of rocks with moderately dipping foliation.

Seismic data is available from two areas within the Archean Wyoming province, the Wind River Mountains which are comprised of some of the oldest rocks of the Wyoming province, and the Laramie Range. The COCORP Wind River lines that imaged the Laramide Wind River thrust fault crossed the flank of a greenstone belt at South Pass (8). Except for one strong event at 2.5 s, the seismic section does not show many reflections from the upper crust. This is somewhat surprising because of the different velocity contrasts expected from within the greenstone belt rocks; however, the explanation for this might be the steep dips that are present near the surface.

The crust beneath the Wind River Mountains produces discontinuous but strong reflections all through the crust and complex arcuate events at 8 s on line 1A (10). Interpretation of these events on the basis of fold structures exposed up-plunge in the hanging-wall block of the Wind River uplift suggests that the deep crust is not significantly different from the folded high grade metamorphic rocks intruded by granites exposed in the core of the range. Furthermore, Smithson et al. (1980) suggest that a crustal thickness of 35-40 km was attained by 3 b.y. based on the interpretation of complex fold structure. Constraints on deep crustal development may best be determined from the reflection data.

A Proterozoic suture zone in southeastern Wyoming marks the border between the Archean Wyoming province (which includes the basement rocks of the Wind River Mountains) and 1.7 b.y. crust to the south (10). The suture zone consists of a steeply dipping mylonite zone from 1 to 7 km wide (10). This area has been the site of extensive geophysical studies including acquisition of seismic reflection and gravity data by the University of Wyoming (11,12) and COCORP seismic lines (13). These data have provided constraints on the interpretation of surficial geological features as well as deep crustal structure. Most of the seismic data comes from the Proterozoic terrain south of the suture zone. Gravity interpretation indicated that charnockitic syenite associated with the Laramie anorthosite complex was underlain at several kilometers depth by mafic rock (14), and later seismic work showed refractions coming from a high-velocity (mafic) zone. Both seismic reflection interpretation (11,13) and gravity interpretation suggest that the Laramie anorthosite itself is about 6 km thick. Reflections from depths of 4 to 18 km are found beneath the vast 1.4 b.y. Sherman granite and indicate the presence of heterogeneities that could represent features such as xenoliths or the base (or far below the base) of the batholith (11).

Many ambiguities still exist in the interpretation of deep crustal reflections. Complexities are illustrated by a zone of reflections resembling an unconformity on COCORP line 5. When this data is migrated to move dipping events into proper geometric position, the reflections then form the shape of a dipping saucer. This could come from a layered mafic intrusion (15), and modeling, which is generally the only check on a deep crustal reflection interpretation, indicates that this is a plausible conclusion (16, Fig. 4, p. 96).

The shear zone marking the Proterozoic suture may have been detected by the COCORP reflection survey which suggests that it dips about 50° southeast (13). Although Moho depths were picked from the COCORP data, the seismic data are highly ambiguous and unreliable on this question. Gravity data, however, indicates a change in crustal structure across the Archean-Proterozoic suture (12). The gravity field decreases to the southeast at the suture zone (Fig. 2) and the interpretation of this observation is that the crust thickens to the south and/or crustal density decreases to the south (12). Because of Laramide effects, some long-wavelength thickening of the crust occurs to the south, but an abrupt change in crustal thickness or change in crustal density or both occurs at the boundary and has apparently persisted since middle Proterozoic time (12). The southern Proterozoic province is believed to consist of deeply eroded roots of a migrating chain of island arcs and a continental margin that evolved from an Early Proterozoic Atlantic-type passive margin to a convergent margin in the Middle Proterozoic with the accretion of island arc terrains (10). This is somewhat similar to the early Paleozoic history of the Appalachians.

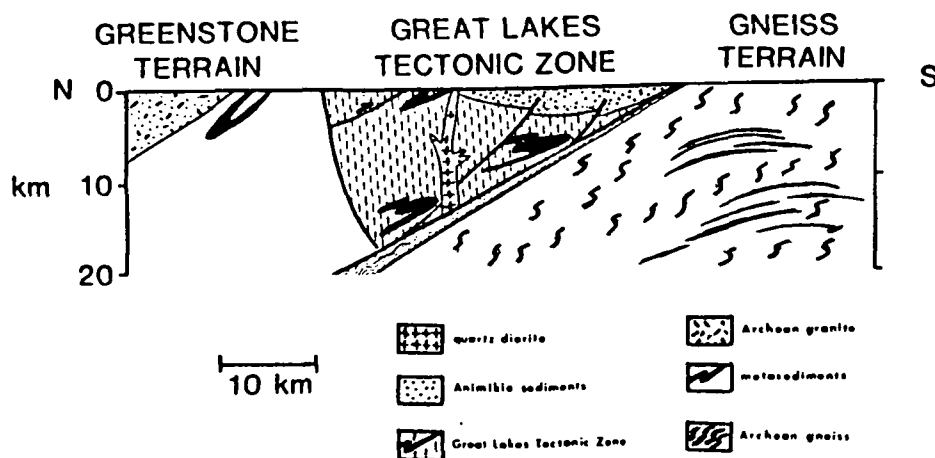


Figure 1. Interpretation of seismic sections showing structural relationships between different terrains in Minnesota Archean separated by a mylonitic thrust zone.

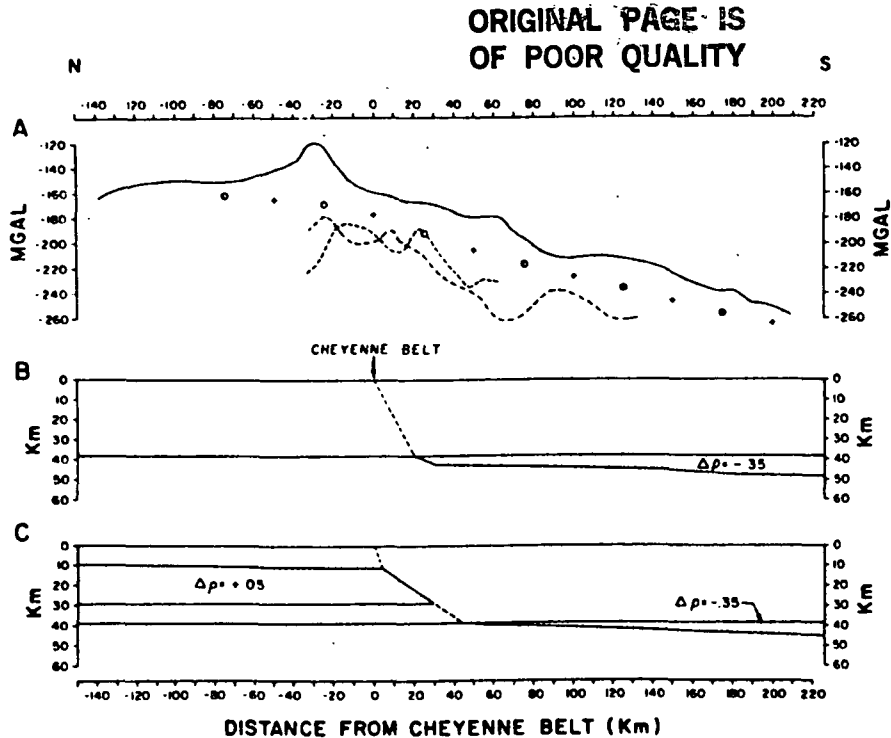


Figure 2. Gravity profiles (A) over Proterozoic suture (Cheyenne belt) in southeastern Wyoming. Profiles are from three different areas and show a general decrease in gravity across the Cheyenne belt. Gravity model B explains the decrease in gravity solely on the basis of a change in crustal thickness and gravity model C combines a change in crustal density with a small change in crustal thickness as an alternative interpretation (After Johnson et al., 1984).

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Pb ISOTOPIC EVIDENCE FOR EARLY ARCHAEOAN CRUST IN SOUTH GREENLAND.

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Early Archaean crust has been positively identified in the Godthaab district of West Greenland - the Amfsoq gneisses, the Isua supracrustals, and the Akilia association - and on the other side of the Davis Straits in the Saglik area of Labrador - the Uivak gneisses etc.. These rock-units have all been directly sampled and dated by a variety of methods.

An indirect method of detecting unexposed ancient crust using Pb isotopic analyses of younger igneous rocks exposed at surface was pioneered by Moorbath & Welke (1) in their study of Tertiary basalts on Skye, N.W.Scotland. Ancient U-depleted Lewisian basement is recognizable as the source of very distinctive unradiogenic contaminant Pb in the basalts. The early Archaean Amfsoq gneisses have a still more distinctive, less radiogenic Pb, and that characteristic has been employed in studies of the late Archaean gneisses of West Greenland - the Nûk gneisses of the Godthaab district, and their temporal equivalents in areas to the north and south of Godthaab - to test for the presence of Amfsoq gneiss at depth (2). Contamination of late Archaean rocks with Amfsoq-derived Pb has been detected as far south as Sermilik. The Nordland-Sukkertoppen granulites show no evidence of contamination with Amfsoq-type Pb; nor do the quartzofeldspathic gneisses at Majorqap Qava in the Fiskenaesset area - the southern limit of that study. Thus Sermilik was identified as the southern limit of inferred early Archaean crust in West Greenland, and the mouth of Godthaabsfjord as the north-western limit.

Over the last few years we have carried out a substantial programme of Pb isotope geochemistry on late Archaean and early Proterozoic rock-units in the southern part of the Archaean craton and the Ketilidian (Proterozoic) mobile belt. Table 1 presents age data and model  $\mu_1$  values for each of the rock-units studied. By comparison with the model  $\mu_1$  values for most other late Archaean - early Proterozoic rock-units, the model  $\mu_1$  values reported in table 1 are ubiquitously low, a characteristic feature of rock-units derived from, or contaminated by, ancient U-depleted crust in which Pb isotopic evolution has been severely retarded. Fig. 1 illustrates the variations in model  $\mu_1$  value with time predicted by Zartman & Doe 'Plumbotectonics' (3) for rock-units derived from their model lower crust, upper crust, mantle, and orogene sources. Note the very low model  $\mu_1$  values for derivation of Pb from the lower crust during late Archaean and early Proterozoic times. The low model  $\mu_1$  values for even the oldest of the analysed rock-units in South Greenland - the gneisses around Ivigtut - imply that this area has been the site for several episodes of reworking of older, U-depleted continental crust.

Table 1.

Locality	Rock-unit	Age (Ma.)	Model $\mu_1$ value
Ivigut	Gneisses	3110 $\pm$ 65	7.19 (6)
Kungmiut	Grey banded gn.	2985 $\pm$ 115	7.47 (6)
Kungmiut	White orthogn.	2769 $\pm$ 110	7.25 (6)
Vesterland	Gneisses	2784 $\pm$ 53	7.21 (6)
Iviangiussat	Gneisses	2734 $\pm$ 130	7.14 (6)
Tornarsuk	Gneisses	2791 $\pm$ 70	6.90 (6)
Torssut	MD3 dolerite	ca. 2150 (*)	6.57 - 6.87 (4)
Ketilidian BZ	Kaerne granite	1775 $\pm$ 25 (*)	7.19 (5)

(\*) Age determined by Rb-Sr whole-rock isochron method.

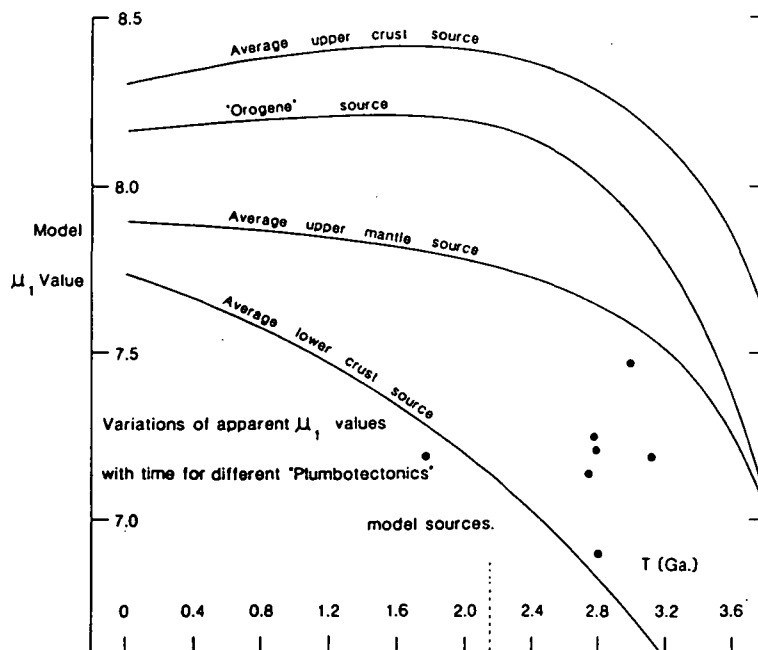


Fig.1. Plot of age & model  $\mu_1$  values for the South Greenland rock-units (Table 1.). Plumbotectonics sources (3) would give magmas with age & apparent  $\mu$  characteristics specified by the four curves in the diagram.



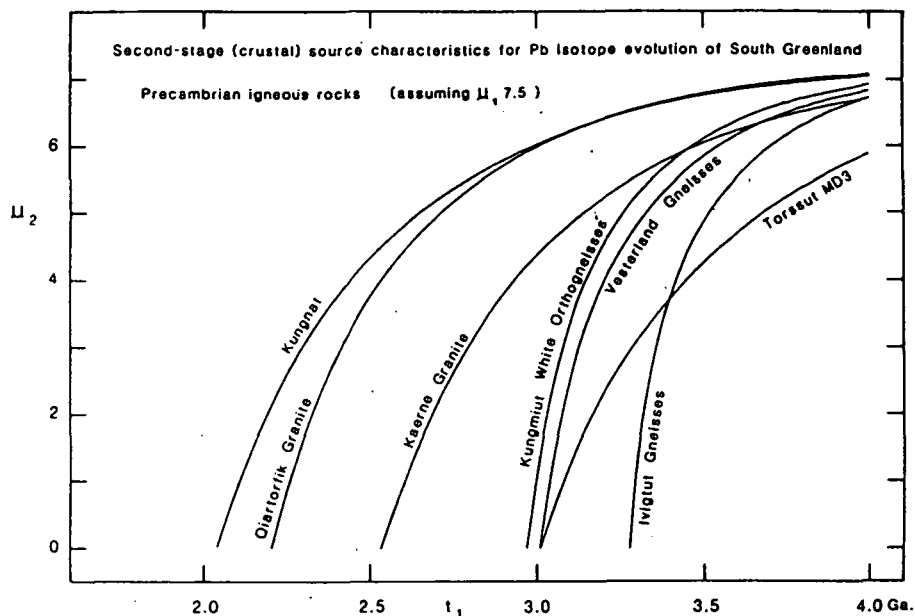


Fig.2. Possible age &  $\mu$  characteristics of the source materials for South Greenland rock-units with low model  $\mu_1$  values.

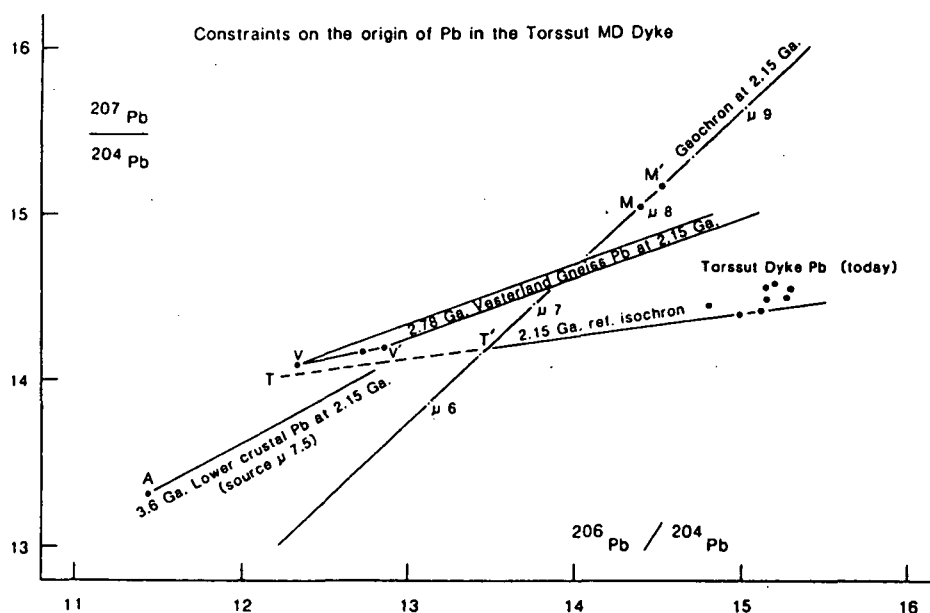


Fig.3. Pb isotope evolution diagram for the Torssut MD3 dolerite dyke, and its country rocks - Vesterland gneisses.

Fig. 2 illustrates possible two-stage model solutions for the isotopic evolution of the initial Pb of some of the South Greenland rock-units, assuming that the lowest viable first stage  $\mu$  value would be  $\sim 7.5$ . This assumption yields minimum estimates for the age of the source of crustal Pb in the rock-units concerned. Thus the  $\sim 3110$  Ma. Ivigtut gneisses must have a source of crustal Pb at least as old as  $\sim 3300$  Ma., and the  $\sim 2150$  Ma. Torssut MD3 dolerite dyke must have acquired its Pb from crust at least  $\sim 3000$  Ma. old. In fact the source of crustal Pb in the Torssut dyke is likely to be significantly older than that minimum of  $\sim 3000$  Ma. for two reasons:

- (i) No continental crust suffers total U-depletion to give  $\mu_2$  values of 0 : finite  $\mu_2$  values require older source ages.
- (ii) Since Torssut is a dolerite dyke, it inevitably has a juvenile ( $\sim 2150$  Ma.) mantle-derived component of Pb : this requires that its source of crustal contaminant Pb must have  $t_1$ ,  $\mu_2$  characteristics plotting below / to the right of the curve for Torssut in fig. 2. (4)

The country rock gneisses to the Torssut dyke had Pb already too radiogenic at  $\sim 2780$  Ma. to provide the contaminant Pb required to account for the Torssut dyke compositions. This point is illustrated in fig. 3, in which it is also shown that Pb of a similar character to that of the Amfsoq gneisses is a very plausible contaminant (4).

Despite extensive studies of gneisses from the southern part of the West Greenland craton, we have yet to discover any direct evidence for the presence of early Archaean rocks at the present surface. However, we consider that the Pb isotopic data discussed above is strong indirect evidence indicating the occurrence of early Archaean U-depleted crust at depth beneath southern West Greenland.

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FLUID-ABSENT METAMORPHISM IN THE ADIRONDACKS.

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Introduction. Granulite facies metamorphism occurred over an area of  $> 20,000 \text{ km}^2$  in the Adirondack Highlands, N.Y., USA and has been dated at  $\sim 1.1$  by. (Grenville Orogeny, ref. 1). Peak metamorphic conditions as determined from numerous geothermometers and barometers in many rock types increase from about  $675^\circ$  at the orthopyroxene isograd in the NW to  $775^\circ\text{C}$  in the Central Adirondacks at  $7.6 \pm 0.5$  kbar (Fig. 1, ref. 2). Low values of water activity ( $\alpha\text{H}_2\text{O}$ ) are demonstrated by assemblages of tremolite + diopside + enstatite + quartz; phlogopite + quartz + enstatite + K-feldspar; annite + K-feldspar + magnetite + ilmenite; and unmelted K-feldspar + plagioclase + quartz. Quantitative estimates from mica and amphibole equilibria yield  $\alpha\text{H}_2\text{O} \approx 0.1$  (3,4,5). Muscovite + quartz assemblages in adjacent amphibolite facies rocks in the NW Adirondack Lowlands indicate high  $\alpha\text{H}_2\text{O}$  demonstrating that the amphibolite to granulite facies transition in the Adirondacks is the result of increasing temperature and decreasing  $\alpha\text{H}_2\text{O}$ .

Causes of low  $\alpha \text{H}_2\text{O}$ . Three processes can account for low  $\alpha \text{H}_2\text{O}$  in granulites: A) large amounts of  $\text{CO}_2$  infiltration where  $\text{H}_2\text{O}$ -rich fluids are diluted by  $\text{CO}_2$  and dehydration reactions for mica and amphibole are driven in the prograde direction (6); B) partial melting with or without the extraction of a magma and where  $\text{H}_2\text{O}$  is partitioned preferentially into the silicate liquid (7); and C) metamorphism of igneous or metamorphic rocks that were already "dry."

The recognition that one of these processes has influenced the formation of a given rock is important in understanding its history because the results of each process can be quite different. Only processes A) and B) can result in large amounts of mass transport such as is necessary to dehydrate a metasediment or cause LIL element depletions. Processes B and C on the other hand can lead to a metamorphic recrystallization in the absence of a free fluid phase where any hydrogen or carbon that may be in a rock during metamorphism is not in the form of an  $\text{H}_2\text{O} - \text{CO}_2$  fluid.  $\text{CO}_2$  infiltration, process A, cannot proceed under fluid-absent conditions.

Fluid-absent metamorphism. Fluid-absence has thus far been demonstrated in two rock types in the Adirondacks. In calc-silicates and marbles adjacent to massif-type anorthosite bodies low values of  $\delta^{18}\text{O}$  ( $-1.3$  to  $3$ ) indicate that low P contact metamorphism preceded granulite metamorphism (8,9). In these rocks numerous wollastonite occurrences indicate low  $\alpha\text{CO}_2$  and in one rock the assemblage monticellite + forsterite + diopside + calcite + spinel indicates  $P \text{H}_2\text{O} + P \text{CO}_2 < 0.5$  kbar at  $P = 7.5$  kbar (Fig. 2). These results, plus the close preservation of pre-regional metamorphic  $\delta^{18}\text{O}$  values, indicate that granulite facies metamorphism was representative of process C where early shallow contact metamorphism volatilized marbles and subsequent granulite metamorphism was fluid-absent.

FLUID-ABSENT METAMORPHISM  
J.W. Valley

Many charnockites in the Adirondacks are also indicated to have been fluid-absent by low, buffered values of oxygen fugacity ( $fO_2$ ) and water fugacity ( $fH_2O$ , ie  $aH_2O$ ). Estimates of  $fO_2$  in Adirondack charnockites from coexisting magnetite + ilmenite (10) are mostly below the quartz + magnetite + fayalite buffer (Fig. 3) and are too low for the stable existence of a  $CO_2$ -rich metamorphic fluid (Fig. 4). These rocks typically contain orthopyroxene + K-feldspar assemblages which also indicate low  $fH_2O$ . Simultaneous solution of C-O-H fluid equations show that at such low  $fO_2$  and low  $fH_2O$  there cannot have been a free C-O-H fluid phase and thus metamorphism was fluid-absent in these rocks (11). Many of these charnockites are clearly indicated by field relations, textures, and geochemistry to be meta-igneous rocks and thus it is reasonable that they experienced fluid-absent metamorphism because they were already "dry." However, this has not been demonstrated in all instances and significant partial melting is likely to also be important.

Recognition of fluid-absence in some Adirondack rocks does not necessarily imply that this entire former portion of the deep crust was lacking in fluids. Assemblages of phlogopite + calcite + quartz and tremolite + calcite + quartz are common and at Adirondack P-T this requires  $P H_2O + P CO_2 \approx 6-8$  kbar (12) suggesting fluid saturation.

This result in no way conflicts with fluid-absence for other rocks if the fluid regime of the deep crust is complex. Sharp gradients in  $\delta^{18}O$  and in buffered fluid compositions (3,8) indicate that fluid conditions in the Adirondacks were locally heterogeneous. Thus it is likely that processes B, C, and possibly A all operated synchronously and possibly in close proximity. However, no evidence of large scale  $CO_2$  infiltration has yet been found in the Adirondacks and even in terranes where strong evidence of  $CO_2$  infiltration has been located in some rocks (6) it is premature to assume that all rocks were affected.

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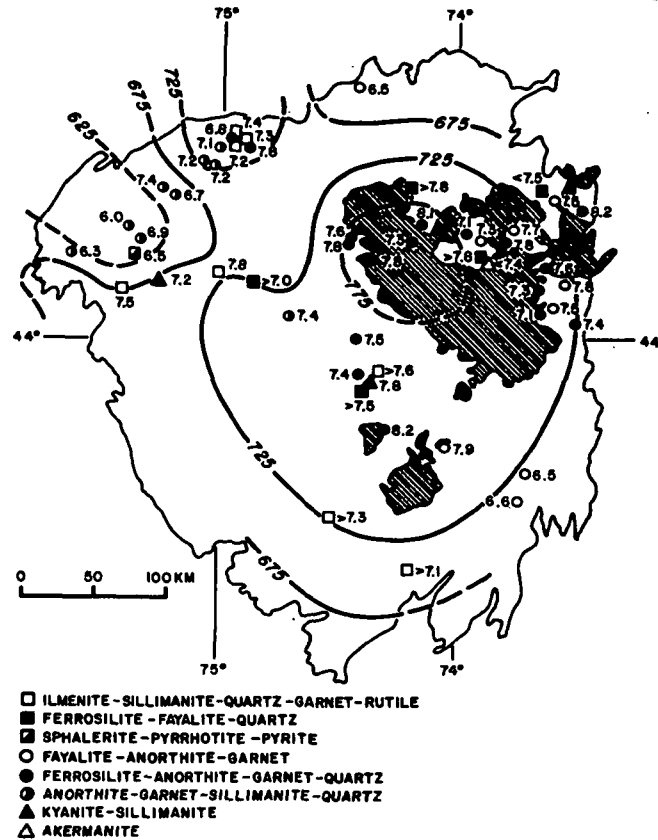


Figure 1. Values of peak metamorphic pressure and temperature in the Adirondacks (ref. 2).

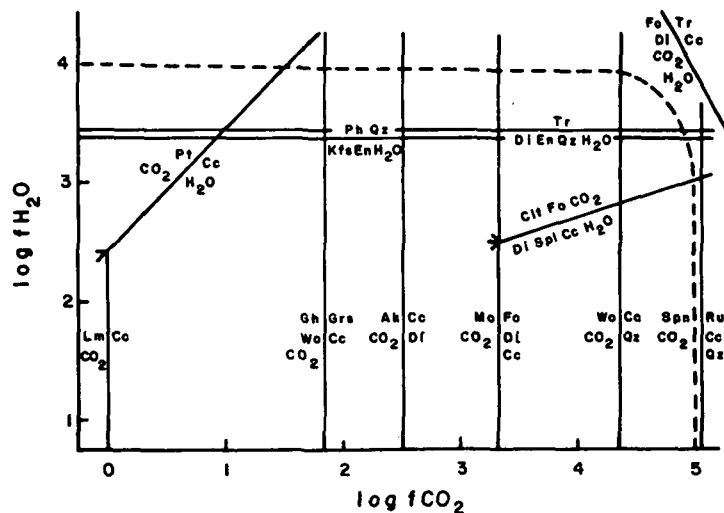


Figure 2. Mineral equilibria buffering  $f\text{CO}_2$  and  $f\text{H}_2\text{O}$  at  $780^\circ\text{C}$  and 8 kbar. The dashed curve represents  $P\text{H}_2\text{O} + P\text{CO}_2 = 8\text{ kbar}$  and fluid-absent conditions plot below or to the left. The fluid-absent assemblage monticellite + forsterite + diopside + calcite + spinel plots at  $\log f\text{CO}_2 = 3.3$ ,  $\log f\text{H}_2\text{O} < 2.5$  (ref. 9).

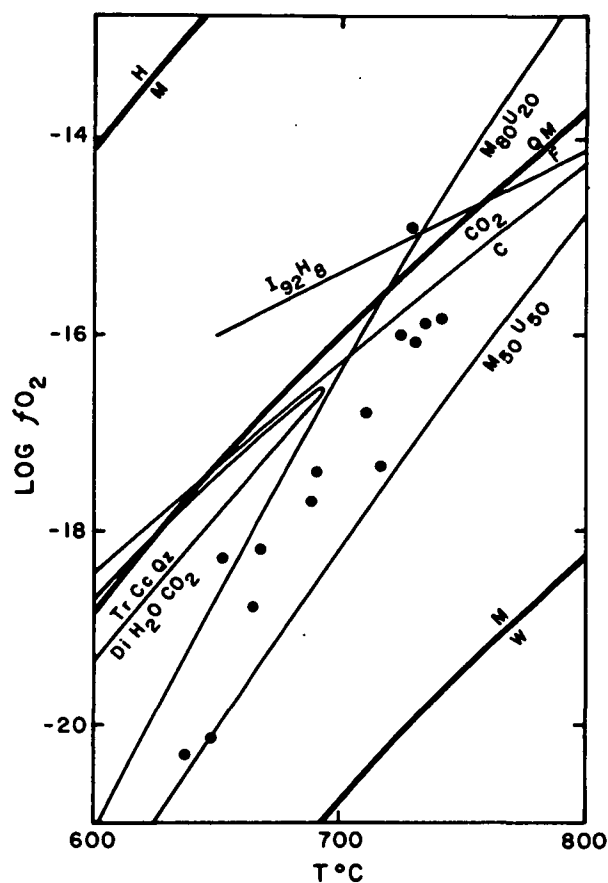


Figure 3. Log  $f_{O_2}$  - T plot at 8 kbar. Data points are from coexisting magnetite + ilmenite (10,13). Abbreviations are: H hematite, Q quartz, M magnetite, F fayalite, U ulvöspinel, I ilmenite, W wüstite, C graphite, Tr tremolite, Cc calcite, Di diopside.

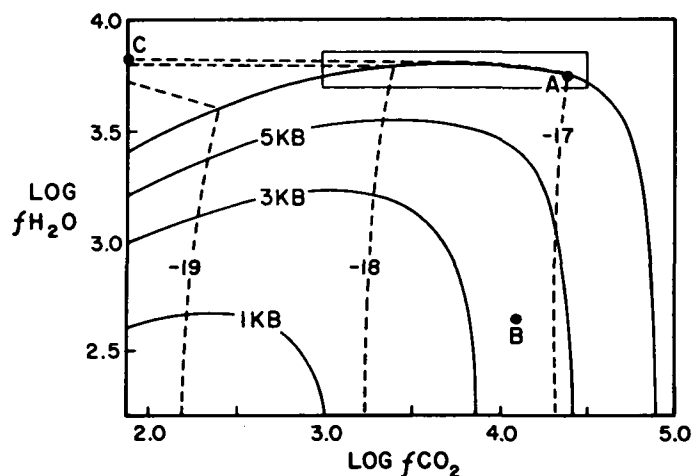


Figure 4. C-O-H fluid equilibria at 700°C, 7 kbar. The outermost curved solid line represents graphite saturation at  $P_{\text{fluid}} = 7$  kbar. Solid isopleths below this curve are the maximum total pressure of all C-O-H fluids possible regardless of the presence or absence of graphite and thus the field below graphite saturation represents fluid-absence unless large amounts of some non C-O-H fluid are present (ref. 11).

FLUID-ABSENT METAMORPHISM  
J.W. Valley

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**THE ARCHEAN GEOLOGY OF THE  
GODTHÅBSFJORD REGION,  
SOUTHERN WEST GREENLAND**

**(Includes Excursion Guide)**

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## INTRODUCTION

[ This account is concerned with the part of the West Greenland Archean gneiss complex centered around Godthåbsfjord and extending from Isukasia in the north to south of Færingehavn. The special significance of this region for understanding crustal genesis in the early history of the Earth includes the following.

(1) Extensive outcrops of 3800–3400 Ma rocks can provide some direct evidence of conditions and processes that operated on the Earth in the early Archean. However, the ways in which primary characteristics have been modified by later deformation, metamorphism, and chemical changes must first be taken into account.

(2) The rocks exposed are the products of two major phases of accretion of continental crust, at 3800–3700 Ma and 3100–2900 Ma. The main features of these two accretion phases are similar, but careful study of the least modified rocks may reveal differences related to changes in the Earth in the intervening period.

(3) The combination of excellent exposure over an extensive area, relatively detailed geological mapping of much of the region, and a considerable volume of isotopic and other geochemical data gives special insight into processes that operated at moderately deep levels of the crust in the Archean. Of particular interest is the effect of late Archean granulite facies metamorphism on early Archean rocks, especially the extent to which isotope systems were disturbed. Similar processes may well have partly or wholly destroyed evidence of more ancient components of other high grade terrains.

Stratigraphic relations and the first-order elements of the chronology were first worked out during the late 1960s, mainly within the area of the Qôrqt 1:100,000 geological map sheet (64 V 1 S). Field mapping of this sheet extended from 1965 to 1979 and much of it was of a reconnaissance nature only, based on coastal outcrops and rather widely spaced traverses inland. Part of the Nordlandet peninsula, the Qôrqt granite complex between Qôrqt and Sulugssugutip kangerdlua, the peninsulas and islands between the mouths of Godthåbsfjord and Ameralik, and some areas on the south side of Ameralik were mapped in greater detail.

The Buksefjorden 1:100,000 map sheet (63 V 1 N) to the south was mapped in considerable detail between 1972 and 1977 (*Chadwick and Coe*, 1983). Most of the sheet was mapped on a scale of 1:20,000, while the Narssaq peninsula and the islands around Qilângârssuit were mapped at 1:10,000. Our field studies and those of *Sharpe* (1975) show that the full extent of early Archean rocks is not shown on the Buksefjorden map sheet.

Field mapping for the Ivisârtoq (64 V 2 N) and Isukasia (65 V 2 S) 1:100,000 map sheets in the northeastern part of the region was carried out from 1981 to 1983. Mapping was less detailed than for the Buksefjorden sheet but benefited from advances in understanding of the regional geology that had been made in the 1970s. Both sheets are in the process of compilation and drafting. Mapping is in progress for the Fiskefjord 1:100,000 map sheet (64 V 1 N) north of the Qôrqt sheet. The Isua supracrustal belt and adjacent gneisses have been mapped in considerable detail by G.G.U. geologists and will be published at 1:40,000.

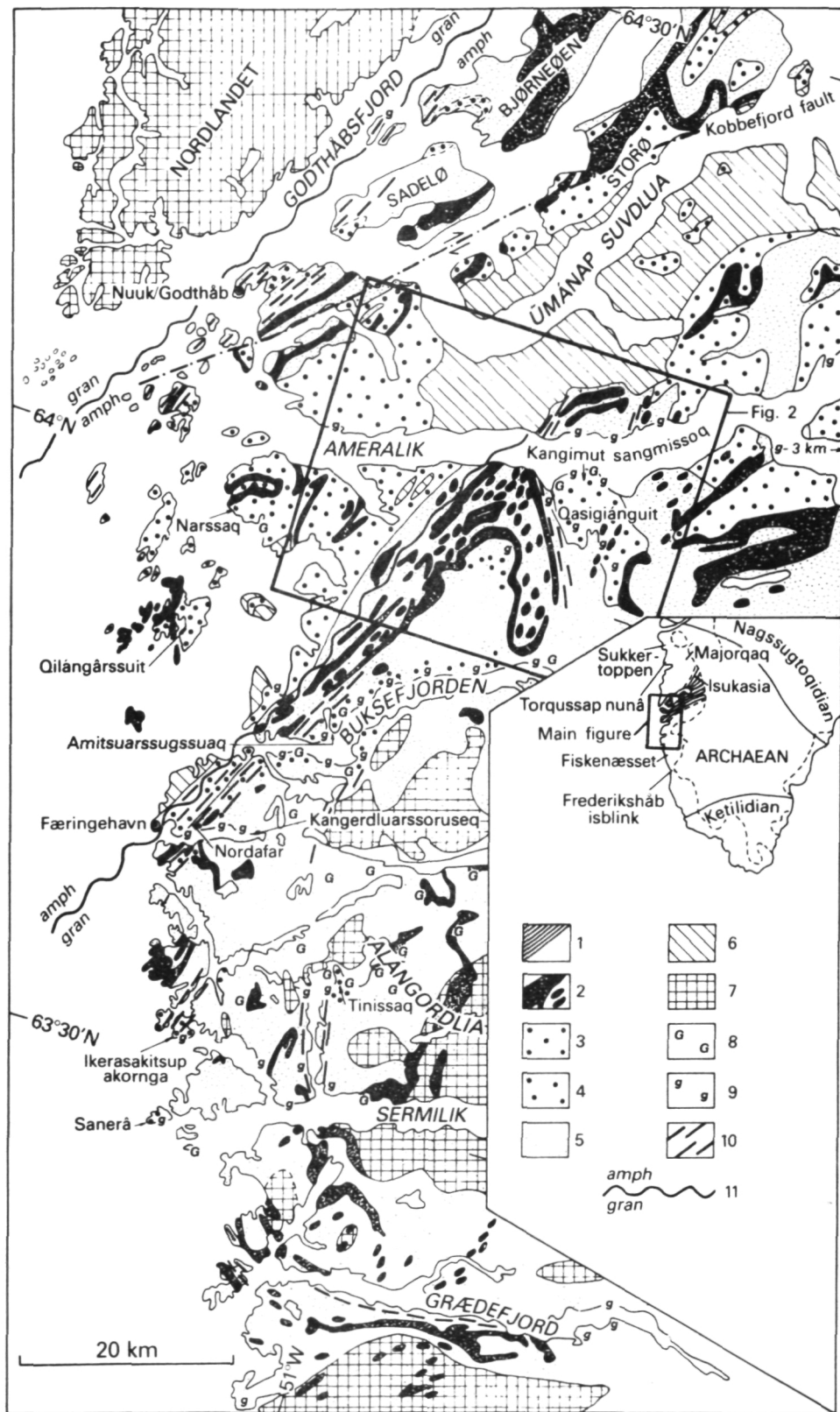
The Frederikshåb Isblink-Søndre Strømfjord 1:500,000 geological map sheet is based on the 1:100,000 map sheets for the whole of the area south of 64°N and for the area of the Qôrqt sheet. The remainder of the map area was compiled from helicopter and coastal reconnaissance in 1976–1978. It does not include the results of mapping for the Ivisârtoq, Isukasia, and Fiskefjord 1:100,000 sheets. No further regional mapping has been done since helicopter reconnaissance in 1976 within the Kapisigdlit 1:100,000 map sheet area (64 V 2 S), east of the Qôrqt sheet. The geology of this part of the region is relatively poorly known.

It is recommended that the reader acquire the 1:100,000 Qôrqt (64 V 1 S) and Buksefjorden (63 V 1 N) and 1:500,000 Frederikshåb Isblink-Søndre Strømfjord geological map sheets in order to follow the description of the geology that follows. These map sheets can be ordered from the Geological Survey of Greenland, Øster volgade 10, DK-1350 Copenhagen K, Denmark. The price per sheet in 1985 was 100 Danish kroner, exclusive of mailing charges.

[ This account does not attempt to be an exhaustive review of all work carried out on the geology of the region. Rather, it attempts to summarize aspects of the geology and some recent speculations on its significance that can be of interest in the context of early crustal genesis. Earlier papers and ideas are referred to only where they have not been superseded by later work. The geology of the Godthåbsfjord region is extremely complex and still far from properly understood. We apologize if the reader becomes lost at times in the details of what follows. We often get lost ourselves.

## EARLY ARCHEAN

An older complex of rocks in the Godthåbsfjord region was separated from younger rocks initially on the basis of a single field criterion: that they contain very abundant tabular bodies of amphibolite derived from basic dikes to which the name Ameralik dikes was given (*McGregor*, 1973). Amphibolites derived from basic



dikes are rare or absent in other lithologic units in the region, and these units were presumed to be younger than the Ameralik dikes. Subsequent isotopic studies showed that the units with abundant Ameralik dikes or, in the Isukasia area, cut by less deformed Tarssartôq dikes, which are at least in part equivalent to the Ameralik dikes, were all formed between about 3800 and 3400 Ma (references elsewhere in this volume).

Early Archean rocks, intercalated with younger rocks, have been recognized with certainty within a tract that extends for 200 km from the margin of the Inland Ice at Isukasia to the outer coast south of Færinghavn. To the southeast, early Archean units are disrupted by increasing amounts of mid- to late Archean gneisses, and they become more difficult to recognize because of more intense late Archean modification. In particular, late Archean granulite facies metamorphism partly erased field evidence for separating early Archean gneisses from younger rocks and destroyed the early Archean isotopic signature (see below). Early Archean rocks extend farther south and southeast than is indicated on the 1:500,000 and the Buksefjorden 1:100,000 map sheets. Rocks that we consider on the basis of field criteria to be early Archean crop out to within 4 km of the head of Buksefjorden and south as far as Tinissaq (*Chadwick et al.*, 1974) and the islands at the mouth of Sermilik (Figure 1). Here they make up only a relatively small proportion of the geology.

Early Archean rocks may be present locally northwest of the Godthåbsfjord region. *Hall* (1977, 1985) noted banded iron formation and other lithologies that suggest early Archean rocks near the margin of the Inland Ice 80 km NNE of Isukasia. Rocks that resemble Amitsoq gneisses and Ameralik dikes form part of Tovqussap nunâ, north of the mouth of Fiskefjord.

Early Archean rocks in northern Labrador (see *Collerson et al.*, 1982, for references) resemble the early Archean rocks in the southern part of the Godthåbsfjord region, and they probably formed parts of the same complex before the opening of the Labrador sea.

In West Greenland the early Archean rocks are best preserved in the Isukasia area, which is described separately (*Nutman and Rosing*, this volume). Throughout the remainder of the tract where they have been recognized, their primary characters have been severely modified by mid- to late-Archean plutonic activity: intense deformation, intrusion of voluminous granitoid magmas, and high-grade metamorphism. The early Archean rocks in the Godthåbsfjord region outside the Isukasia area comprise the *Akilia association* of supracrustal and basic to ultrabasic intrusive rocks and the younger and much more voluminous *Amitsoq gneisses* that intrude them.

### AKILIA ASSOCIATION

Fragments of older rocks occur throughout the region within the Amitsoq gneisses. Except for the rocks of the Isua supracrustal belt, they are all grouped for convenience under the term Akilia association (*McGregor and Mason*, 1977). The range of Akilia lithologies is similar throughout the region and there are similarities with especially the lowest part of the Isua supracrustal sequence. There is no indication that rocks of more than one age group are involved. It seems most probable that the Isua supracrustal belt and all of the Akilia supracrustal rocks are parts of a single sequence that was "exploded" by intrusion of the parents of the Amitsoq gneisses.

Individual bodies of Akilia rocks range in size from very small up to mappable units hundreds of meters thick that can be followed for kilometers. Especially extensive units crop out northeast of Qôrqt and between the Isukasia area and the head of Godthåbsfjord.

*Nutman* (1980) grouped Akilia rocks SSW of the mouth of Ameralik into (1) an early assemblage of interlayered amphibolites, banded iron formations, and felsic gneisses of probably volcanic and sedimentary origin; (2) massive leucogabbroic rocks intrusive into (1); and (3) layered ultramafic rocks.

Fig. 1. Geological sketchmap of the southern part of the Godthåbsfjord region and the northern part of the Fiske-næsset region; (1) Belt of rocks not affected by granulite facies metamorphism in the late Archean; (2) Mid-Archean supracrustal and anorthositic rocks; (3) Early Archean rocks, mainly Amitsoq gneisses; (4) Areas with early Archean rocks extensively intruded by mid- to late Archean gneisses; (5) mid- to late Archean gneisses (Nûk gneisses and equivalents); (6) Qôrqt granite complex; (7) Areas with granulite facies mineral assemblages; (8) Localities with mineralogical evidence (relic orthopyroxene) of late Archean granulite facies metamorphism in rocks mainly retrogressed to amphibolite facies; (9) Localities with textural evidence of late Archean granulite facies metamorphism in retrogressed rocks; (10) Post-granulite facies deformation belts; (11) Approximate position of original late Archean prograde granulite-amphibolite facies boundaries.

Rapid variations occur within the rocks of group (1), which is dominated by basic lithologies. These comprise layered mesocratic amphibolites with Fe-rich tholeiitic affinities and rocks that range from pyroxene-bearing amphibolites to clinopyroxenites. The pyroxene-bearing layered basic rocks have high MgO, Cr, and Ni and low  $\text{Al}_2\text{O}_3$ ,  $\text{TiO}_2$ , and  $\text{Na}_2\text{O}$ . *McGregor and Mason* (1977) concluded that they were chemically comparable to the komatiitic association but considered it possible that at least some were of cumulate origin. No primary igneous textures are preserved in them. *Nutman et al.* (in preparation) question whether any of these rocks crystallized from komatiitic liquids and suggest that all or most of them are derived from tholeiitic magmas in which olivine and orthopyroxene had accumulated.

The metasedimentary rocks are mostly quartz-rich pyroxene-, amphibole-, magnetite-, and garnet-bearing rocks in which graphite, biotite, molybdenite, and carbonate occur locally. They are interpreted as derived from varieties of banded iron formation with possible associated chert. Less common are rusty-weathering biotite-garnet-feldspar gneisses, locally associated with quartz-rich gneisses, that are thought to be derived from acid to intermediate volcanics or from feldspathic detrital sediments. Some quartz-rich layered rocks appear to be the result of secondary introduction of silica.

The leucogabbroic rocks of group (2) form sheets intruded into the volcanic-sedimentary sequence. Locally there is poorly developed layering interpreted as of primary igneous origin, for example, on SE Qilángårssuit where this unit contains anorthositic layers. The composition of fine-grained homogeneous varieties may to a first approximation be that of liquids and resembles strongly fractionated "komatiitic" liquid compositions.

The ultramafic rocks (3) are mainly meta-peridotites. Olivine has been partly or completely hydrated and occurs as relics associated with pyroxene, tremolitic amphibole, talc, serpentine, and phlogopite. These rocks are interpreted as derived from cumulate facies of the layered basic rocks.

Extensive units of Akilia association rocks between the mouth of Ameralik and the head of Godthåbsfjord have not been studied in any detail and could well repay investigation.

## AMÏTSOQ GNEISSES

This term is used for all quartzofeldspathic gneisses in the Godthåbsfjord region that contain abundant amphibolites derived from basic dikes or that, in the Isukasia area, are cut by Tarssartôq dikes. Wherever these rocks have been studied isotopically between Storø, in Godthåbsfjord, and the islands northwest of the mouth

of Buksefjorden, as well as in the Isukasia area (references in *Nutman and Rosing*, this volume), they have yielded early Archean ages by Pb/Pb and Rb/Sr whole rock isochron methods (*Black et al.*, 1971; *Moorbath et al.*, 1972; *Griffin et al.*, 1980) and by U/Pb and Th/Pb zircon methods (*Baadsgaard*, 1973). Sample suites used in the earlier isotopic studies were collected before the polygenetic nature of the Amîtsoq gneisses was investigated in detail. Later studies of better preserved rocks from the Isukasia area (*Baadsgaard*, 1983, and unpublished data), show that the various phases that make up the Amîtsoq gneisses were intruded episodically over a period between 3750 and 3400 Ma. The approximate Rb/Sr and Pb/Pb whole rock isochrons obtained from the mixed suites collected in the late 1960s and early 1970s are probably to a considerable extent the result of high-grade metamorphism, reaching granulite facies grade in the south, that affected most of the Amîtsoq gneisses ca. 3600 Ma ago (*Griffin et al.*, 1980).

Most of the Amîtsoq gneisses are highly deformed, layered grey gneisses, commonly with abundant thin pegmatitic layers. Layered gneisses of this type are seen in the Isukasia area to be the products of intense deformation of polyphase parents that include an early tonalitic suite intruded 3750–3700 Ma ago, a granitic suite intruded into the tonalitic gneisses at ca. 3600 Ma, and minor pegmatitic sheets emplaced around 3400 Ma (*Nutman and Rosing*, this volume). The intense deformation erased original discordant contacts between the different phases and smeared out individual bodies into thin concordant layers. In many places it was accompanied by metamorphic differentiation and segregation of pegmatitic material into discrete thin layers. Thus most of the Amîtsoq grey gneisses outside the least deformed part of the Isukasia area have lost almost all of their primary characters. Homogeneous phases that preserve some primary characters do occur locally outside the Isukasia area in small areas of low strain.

South of the mouth of Ameralik, a geochemically distinct iron-rich suite of augen and ferrodioritic gneisses makes up ~ 30% of the Amîtsoq gneisses (*Nutman et al.*, 1984). These rocks are generally more homogeneous and preserve more primary features than grey gneisses in the same area. Contacts between them and the grey gneisses are everywhere concordant, but several lines of evidence suggest that the iron-rich suite was intruded as sheets into the layered grey gneisses.

The ferrodioritic gneisses occur as strips within the augen gneisses. Locally they grade into augen gneisses over several tens of meters, but elsewhere they form sharply bounded inclusions within them. The two



lithologies are interpreted as having been emplaced more or less contemporaneously. The augen gneisses form sheets up to 200 m thick that can be traced for as much as 15 km. Their composition ranges from dioritic to granitic with potassic granodiorite most abundant. Granodioritic and granitic varieties contain abundant augen derived from microcline megacrysts. In the least deformed rocks these megacrysts are up to 2 cm long and may be randomly oriented. Compositional layering is interpreted as deformed igneous layering.

Geochemical studies suggest that the parents of the augen gneisses were the products of mixing of granodioritic melts of deep crustal origin with fractionated basic melts of mantle origin. The ferrodiorites are interpreted as strongly fractionated, crystallized parts of basic intrusions that were carried up to higher crustal levels within the heterogeneous plutons. The Amîtsoq iron-rich suite resembles post-orogenic granitic complexes from younger epochs such as the mid-Proterozoic rapakivi granite suites.

Homogeneous tonalitic gneisses that appear to be younger than the layered grey gneisses form discrete mappable bodies on some islands south of the mouth of Ameralik. Their relations to the iron-rich suite are not known. Sheets of trondhjemitic and granitic gneiss up to 20 m thick cut rocks of the iron-rich suite and adjacent layered grey gneisses. They are only a very minor component of the Amîtsoq complex and are interpreted as crustal melts of local origin.

### EARLY ARCHEAN GRANULITE FACIES METAMORPHISM

Granulite facies mineral assemblages are preserved very locally within rocks of the Akilia association and the Amîtsoq iron-rich suite on islands northwest of the mouth of Buksefjorden (Griffin *et al.*, 1980). We have found relic textures that we consider to have formed under granulite facies conditions in Amîtsoq gneisses and inclusions in them between the Teltøerne, just south of Færingehavn, and Qôrqu in Godthåbsfjord. All of these localities are outside the terrain affected by granulite facies metamorphism in the late Archean (see below). There is no evidence of granulite facies metamorphism in intercalated Malene supracrustal rocks.

Mafic augen gneisses with partly retrogressed granulite facies mineral assemblages from a small island west of the mouth of Buksefjorden give well-fitted Rb/Sr and Pb/Pb whole rock isochrons that yield dates of  $3560 \pm 140$  Ma and  $3625^{+125}_{-135}$  Ma, respectively (Griffin *et al.*, 1980). This shows that the granulite facies metamorphism occurred no later than ca. 3600 Ma ago, since granulite

facies metamorphism is normally accompanied by movement of U and Rb. Zircons from Akilia association rocks affected by early granulite facies metamorphism from a number of localities yield a concordia intersection age of  $3587 \pm 38$  Ma, while zircons from the Isua supracrustal belt yield a concordia intersection age of  $3813^{+24}_{-14}$  Ma (Baadsgaard *et al.*, 1984). There is no reason to believe that the Akilia rocks are younger than those of the Isua supracrustal belt, and the Akilia intercept age is considered to be the result of resetting of the zircons by the early granulite facies metamorphism. Zircons from Amîtsoq gneisses affected by early granulite facies metamorphism from localities south of the mouth of Ameralik yield U-Pb and Th/Pb concordia intercept ages of  $3600 \pm 50$  Ma and  $3550 \pm 85$  Ma, respectively (Baadsgaard, 1973; recalculated with new constants by Baadsgaard *et al.*, 1976). Four of the six samples were from the iron-rich suite, one was from a late sheet cutting augen gneiss and one was from a late homogeneous tonalite. A Lu/Hf age of  $3550 \pm 220$  Ma was reported by Pettingill and Patchett (1981) for a collection of Amîtsoq gneiss samples belonging almost entirely to the iron-rich suite and closely associated late phases.

Intrusive suites that are chemically similar to the Amîtsoq iron-rich suite are commonly closely associated in time and space with granulite facies metamorphism, for example the 2800 Ma Ilivertalik augen granite suite in the Fiskenaeset region to the south (see below). The Amîtsoq iron-rich suite is restricted to areas affected by the ca. 3600 Ma granulite facies metamorphism and it is likely that the two phenomena were connected.

By 3600 Ma the continental crust of which the early Archean rocks in this region formed a part was at least 20 km thick, had a geothermal gradient of  $30^\circ\text{C}/\text{km}$  (Griffin *et al.*, 1980) and had developed a chemical stratification through anatexis and movement of granitic magmas to higher crustal levels. This early Archean sial thus had many features in common with sialic crust that stabilized later in the Earth's history, particularly toward the end of the Archean.

### AMERALIK DIKES

This term is used for the abundant tabular bodies of massive, homogeneous amphibolite derived from basic dikes that occur within early Archean rocks in the Godthåbsfjord region. Less deformed, unbroken basic dikes, at least in part equivalent to the Ameralik dikes, that cut early Archean rocks in the Isukasia area are termed Tarssartôq dikes (Nutman *et al.*, 1983).

Ameralik dikes occur every few meters or tens of meters across the strike in most outcrops of early

Archean rocks outside the Isukasia area. Tarssartôq dikes in the least deformed parts of the Isukasia area are much more widely spaced. This probably reflects telescoping of the rocks by more intense deformation outside the Isukasia area. Most Ameralik dikes are less than 2 m thick, while Tarssartôq dikes are commonly 20–100 m thick. The contacts of most Ameralik dikes have been rotated by intense deformation into concordance with the layering of the enclosing rocks. Most Ameralik dikes are strongly folded and broken up.

There is no compelling reason to believe that the Ameralik dikes are all genetically related or that they were intruded within a relatively short period of time. *Chadwick* (1981) grouped Ameralik dikes between the mouths of Buksefjorden and Ameralik into a number of different types on the basis of field and petrographic characters. A small proportion of Ameralik dikes, shown by rare intersections to be among the older dikes, contain white plagioclase clots that in some of the least modified dikes are seen to be derived from euhedral megacrysts of calcic plagioclase. The plagioclase clots are commonly concentrated in trains nearer one margin of the dikes, suggesting flotation in nonvertical bodies (*Nutman*, 1980). We have not observed comparable plagioclase clots in any other basic lithology in the region and have found them to be a particularly useful indicator of highly modified Ameralik dikes and thus of early Archean units. *Chadwick et al.* (1983) reported plagioclase aggregates in a small number of metamorphosed basic dikes in the Ivisârtoq area that they considered to be younger than Ameralik dikes. We are, however, skeptical about their interpretation of the field relations.

The chemistry of Ameralik dikes between the mouths of Buksefjorden and Ameralik was studied by *Chadwick* (1981) and that of a compositionally more restricted collection of Ameralik dikes, including Tarssartôq dikes, from the whole region by *Gill and Bridgwater* (1976, 1979). Most of the dikes have low-K tholeiitic affinity but are commonly iron-rich. However, ultramafic dikes also occur (*Chadwick*, 1981; *Gill et al.*, unpublished data).

The Ameralik dikes cut rocks that 3600 Ma ago formed part of a body of sialic crust with typical continental thickness. *Gill and Bridgwater* (1979) pointed out that there were no recent examples of low-K tholeiitic magmas intruded into the interior of a large sialic crustal segment, except where there was rifting in the initial stages of sea-floor spreading. The Ameralik dikes were intruded after ca. 3400 Ma (the age of Isukasia area Amitsoq pegmatites) but before intrusion of the first Nûk gneisses ca. 3100 Ma ago. They may well have been intruded toward the end of this period, after the

continental mass that included the Amitsoq gneisses had been thinned tectonically and by erosion, near what subsequently became the rifted margin of a continent.

## MALENE SUPRACRUSTAL ROCKS

This term is used for all mid-Archean supracrustal rocks (formed at the surface, i.e., of sedimentary or volcanic origin) in the Godthåbsfjord region.

### 1. Stratigraphic Relations

It was originally thought that Malene supracrustal rocks were not cut by basic dikes like the Ameralik dikes (*McGregor*, 1973). Metamorphosed basic dikes have subsequently been found cutting some Malene lithologies, although they are not nearly as abundant as Ameralik dikes within the early Archean rocks (*Chadwick*, 1981; *Friend and Hall*, 1977). The apparent scarcity of amphibolites derived from basic dikes within the basic Malene units may be more apparent than real, since deformation and metamorphism would have transformed most basic dikes into thin, concordant layers of homogeneous amphibolite. Amphibolites derived from basic dikes are absent or rare in most Malene metasedimentary units.

The chemical similarity of basic dikes cutting Malene supracrustal rocks and of homogeneous Malene amphibolites to the most common types of Ameralik dikes has been considered to support the idea that at least some of the Ameralik dikes were feeders to the lower, basic part of a Malene sequence laid down on a basement of Amitsoq gneisses (*Chadwick*, 1981; *Nutman and Bridgwater*, 1983). However, these chemical similarities are common to the majority of Archean basic rocks in other terrains and other situations, including many greenstone belts (*Gill*, 1979; *Gill and Bridgwater*, 1979).

Malene supracrustal units enclosed in Amitsoq gneisses are very extensive, even where they are quite thin. Contacts with Amitsoq gneisses that are not modified by the intrusion along them of Nûk gneisses, pegmatites, etc. are generally concordant and sharp. At least some Malene-Amitsoq contacts are modified thrusts, since Malene lithologies are cut out when followed along them (*Chadwick and Nutman*, 1979), and successive Malene units within the composite Malene-Amitsoq pile have different lithological associations (*McGregor*, 1975). Northeast of Godthåbsfjord, Malene amphibolites in which the way-up is indicated in places by little-deformed pillow-lava structures are overlain stratigraphically by Amitsoq gneisses (*Hall and Friend*, 1979; *Chadwick*, 1985). One

of the contacts between these two units must therefore be a thrust, yet there is no mylonitization or brecciation and S fabrics are no more intense than in the gneisses and Malene rocks distant from the contact. In places there is a thin layer of biotite schist with quartz nodules along the contact.

*Chadwick and Nutman (1979)* and *Nutman and Bridgwater (1983)* have argued that certain contacts between Malene and Amitsoq units on the islands between the mouths of Ameralik and Buksefjorden are parts of a deformed unconformity. This is based on the following: (a) The presence of thin units of brown, micaceous gneiss and quartz-rich lithologies between Malene amphibolites and Amitsoq gneisses. These can be followed for hundreds of meters along parts of the contact and are interpreted as being derived from basal sediments (arkoses, detrital quartzites, and cherts) that were deposited on a basement of Amitsoq gneisses. (b) Lack of veining, intense shearing, mylonitization, or interdigitation along the generally sharp contact. (c) Several lines of evidence that suggest that the Malene amphibolites lie stratigraphically below the Al-rich paragneisses that are the other major component of the Malene unit on the southern islands. (d) Local truncation of migmatitic veins in Amitsoq gneisses by sharp contacts to Malene amphibolites. This evidence is compatible with the interpretation that these Malene units were laid down as a cover sequence on a basement of Amitsoq gneisses, but it does not prove it. It remains a possibility that all Malene-Amitsoq contacts are thrusts.

Malene paragneisses on Rypeø have REE patterns and abundances (*Dymek et al., 1983; McLennan et al., 1984*) that suggest derivation from rocks like the tonalitic gneisses that are the dominant lithology in both the Amitsoq gneisses (*O'Nions and Pankhurst, 1974; Nutman et al., 1984*) and the type Nûk gneisses (*J. G. Arth, unpublished data*). Sm/Nd characteristics of two samples of the Rypeø paragneisses do not indicate contributions to the parent sediments from early Archean rocks (*Hamilton et al., 1983*). As yet unpublished ion probe studies at Cambridge University have identified early Archean zircons in Malene paragneisses, but indicate that the provenance of the sediments also included contemporaneous (felsic?) igneous rocks.

## 2. Lithologies

(a) *Amphibolites* are the most abundant lithology. Deformation has been so intense in most places that primary structures have been destroyed or modified beyond recognition. Pillow structures are preserved on Ivisârtoq both in amphibolites and in subordinate, but intimately associated ultramafic horizons (*Hall, 1980,*

1981). Here, as elsewhere in the West Greenland Archean (e.g., *Myers, 1978*), intense deformation of basic pillow lavas and associated pillow lava breccias and agglomerates produced finely layered ("striped") amphibolites such as those that make up about half of the Malene amphibolites in other areas. A common variety of striped amphibolite has discontinuous layers and lenses that contain varying proportions of hornblende, diopside, and epidote in addition to plagioclase, and locally also garnet, scapolite, and carbonate. In the Ravns Storø supracrustal belt in the southern part of the Fiskenaeset region similar rocks can be followed into pillow lavas in which the pillow centers have been altered to Ca-rich compositions (*Friend, 1975*). Larger bodies of calc-silicate-rich (skarn) lithologies occur locally within Malene amphibolite units. For example, layers of diopside-scapolite-epidote-sphene rocks are common in the Malene unit at Narssaq south of the mouth of Ameralik. It is reasonable to assume that the striped Malene amphibolites are mainly derived from basic volcanic parents, many or all of which were erupted under water.

Concordant sheets of homogeneous amphibolite, some rich in garnet, that are interlayered with the striped amphibolites are assumed to be derived from thick basic flows, sills, or dikes that have been rotated into concordance by deformation.

*Hall (1980, 1981)* found a continuum in the chemistry of the pillowed Malene rocks on Ivisârtoq from tholeiitic to basaltic and pyroxenitic komatiite compositions, while *Chadwick (1981)* reported low-K tholeiitic chemistry for homogeneous Malene amphibolites between the mouths of Buksefjorden and Ameralik.

(b) *Ultramafic rocks* occur as sheets and pods within Malene amphibolite units and along the contacts of some units with Amitsoq gneisses. They are most extensive west of the thick Malene unit on Sadelø and Bjørneøen in Godthåbsfjord where this unit is intruded by Nûk gneisses.

(c) *Quartz-garnet-sillimanite and quartz-cordierite-anthophyllite gneisses* form what is interpreted as the stratigraphically higher part of the Malene unit on the islands northwest of the mouth of Buksefjorden (*Beech and Chadwick, 1980*). Quartz-garnet-sillimanite gneisses associated with thin, nonpersistent units of marble, green mica gneiss and gedrite-magnetite rock overlie Malene amphibolites and locally contain structures interpreted as cross-bedding. They are in turn overlain by quartz-rich cordierite-anthophyllite-mica gneisses that contain lenses and thin layers of cordierite-anthophyllite-staurolite rocks. What may well be the same unit crops out on the east side of the type Malene unit on Store Malene and the islands to the south. Similar rocks form

part of a thick unit of Malene paragneiss in central Ameralik (Roberts, 1979).

These gneisses are generally depleted in CaO, Na<sub>2</sub>O, and K<sub>2</sub>O and enriched in MgO and Al<sub>2</sub>O<sub>3</sub> compared with all common sediment types. They have very high contents of incompatible trace elements such as Y, Zr, and Nb reflected in high contents of zircon and niobian rutile (Dymek, 1983). Some combination of processes that reworked altered mafic volcanic rocks may have been involved in their genesis. Beech and Chadwick (1980) discussed the chemistry of these gneisses in considerable detail and concluded that the parent sediments could have been mixtures of quartz and Mg-rich clay minerals. On the basis of zircon morphologies, they suggested a detrital origin for the quartz. Higher iron contents and the presence locally of disseminated magnetite and gedrite-magnetite lenses suggest precipitation of additional iron in the parent sediments of the quartz-garnet-sillimanite association. Friend (1975) discussed the origin of similar rocks in the southern part of the Fiskenæsset region.

(d) *Mica-rich and quartzofeldspathic metasediments* of probably detrital origin form part of several Malene units. Quartz-plagioclase-biotite gneisses with smaller quantities of sillimanite, muscovite, microcline, and garnet that crop out on Rypeø have been described in some detail by Dymek et al. (1983). No primary sedimentary structures have been recognized, but the considerable lithological variation and general arkosic composition were considered to indicate heterogeneous sedimentary protoliths, possibly alternations of sandy, silty, and muddy sediments in a near-shore environment.

A lens of graphite-bearing mica schist enclosed in Malene amphibolites on the north side of Kobbefjord has REE and other chemical characteristics that suggest derivation of the parent sediments from basic igneous material like the protoliths of the Malene amphibolites (McLennan et al., 1984). Rusty-weathering garnet-mica-graphite-bearing gneisses on northern Storø in Godthåbsfjord make up one of the largest bodies of Malene paragneisses. Their trace element chemistry suggests a mixed source of mafic volcanics with felsic volcanics and/or tonalitic gneisses (McLennan et al., 1984.).

### 3. Age

A minimum age for the type unit of Malene supracrustals is given by the fact that on southeast Bjørneøen this unit is intruded by tonalitic Nûk gneisses that have yielded zircon ages of 3070 and 3020 Ma (Baadsgaard and McGregor, 1981).

Rb/Sr whole rock dating of Malene supracrustal rocks yielded a scatter between 2500 and 2800 Ma reference isochrons (unpublished Oxford University data). Zircons from Malene metasediments have given a wide range of ages between 2580 and 2960 Ma (Baadsgaard, 1976), which like the Rb/Sr systematics, are considered to be the result of metamorphism.

### 4. Depositional Environment

There is a larger variety of lithologies and more rocks of sedimentary origin in the mid-Archean supracrustal rocks in the Godthåbsfjord region than in most other parts of the West Greenland Archean. Most of the Malene supracrustal rocks, including amphibolites of basic volcanic origin, appear to have been laid down under water. The chemistry of the best preserved Malene basic rocks is similar to that of mid-Archean supracrustal amphibolites in the southern part of the Fiskennæsset region (Friend et al., 1981) where there is no evidence of early Archean rocks. Supracrustal rocks of dominantly basic volcanic origin are the oldest rocks recognized in the Fiskennæsset region and have been interpreted as fragments of Archean oceanic crust (Rivalenti, 1976; Weaver et al., 1982). Friend et al. (1981) suggested that the Malene supracrustal rocks in the Godthåbsfjord region may have been primitive oceanic material that overlapped onto the margin of a continent made of Amîtsoq gneisses. Nutman and Bridgwater (1983) suggested that some of the Malene units may have been deposited on a thinned Amîtsoq basement in a zone of ensialic rifting. This is remarked on further in the section below on mid-Archean crustal structure.

## ANORTHOSITIC COMPLEXES

Anorthositic rocks, strongly broken up by later gneisses, occur semicontinuously for more than 150 km from the outer coast at Tre Brødre through Kangerdluarssoruseq (Færingehavn), outer Buksefjorden, Ameralik, Itivleq, Kapisigdlit kangerdlua, Storø, and Kangiussap nunâ to Ilulialik in inner Godthåbsfjord. Although the anorthositic rocks along much of this tract have been reduced to thin slices and trains of inclusions in the gneisses, it is probable given the large strains suffered subsequently, that they could be all derived from a single layered intrusive sheet. Anorthositic rocks northeast of the head of Ameralik (Nutman, 1982) may also be part of the same sheet.

Where they have not been modified by later intrusions, the contacts of the anorthositic complex are with Malene



supracrustal rocks, or, northeast of the head of Ameralik, with Malene supracrustal rocks and Amitsoq gneisses (Nutman, 1982). In the Godthåbsfjord region no intrusive contacts have been found. Meta-leucogabbros and meta-anorthosites are the most abundant lithology and are associated with smaller amounts of amphibolites derived from gabbros that contain layers of olivine-hornblende ultramafics. The gabbro-derived amphibolites formed the marginal phases of the complex and occur between the anorthositic-leucogabbroic rocks and the enclosing Malene supracrustal or Amitsoq gneiss units. In places they have been mistaken for supracrustal amphibolites. Relic cumulate textures are commonly preserved in the less deformed leucogabbros. Only the anorthositic rocks in the Tre Brødre and Færingehavn areas have been studied in any detail (Sharpe, 1975; summarized by Chadwick and Coe, 1983).

Anorthositic rocks in the Fiskenaeset region crop out within an area some 40 km wide and at least 100 km long. They are considered to be parts of a single layered sheet, termed the Fiskenaeset Complex, that was intruded into submarine basic volcanic rocks and subsequently broken up by granitoid sheets, now gneisses, and complexly folded (see Myers, 1981 and 1985a; for recent summaries of the geology and literature). Windley (1970) likened the Fiskenaeset anorthositic rocks to lunar anorthosites and suggested that they might be part of the Earth's primordial crust. Windley and Smith (1976) compared them with early cumulate rocks in calc-alkaline batholiths of Cordilleran type. Neither of these interpretations has been supported by subsequent work. The Fiskenaeset Complex is now considered to be a layered tholeiitic cumulate that is genetically related to the basic volcanic rocks into which it was intruded (Weaver et al., 1981; Myers, 1976, 1985a). The primary magma is deduced to have been a moderately aluminous tholeiitic basalt, which may have been generated by hydrous fusion of previously depleted mantle and which underwent crystal fractionation under low pressure conditions (Weaver et al., 1981).

The southernmost outcrops of the Godthåbsfjord-Buksefjorden anorthositic complex are 55 km from the nearest outcrops of the Fiskenaeset complex. There are many similarities between the two. One notable difference is that chromitites are a characteristic feature of the Fiskenaeset complex throughout most of its extent but have not been observed in the Godthåbsfjord-Buksefjorden anorthositic rocks.

Anorthositic rocks with relic coarse-grained cumulate textures crop out extensively on western Nordlandet. They were intruded into dominantly basic supracrustal rocks and are extensively broken up by later intrusive rocks of dioritic and trondhjemitic compositions. Meta-

leucogabbro rather than meta-anorthosite is the dominant lithology, and there may be a transition in composition between these and the dioritic gneisses that intrude them. Together with their country rocks, the Nordlandet leucogabbros preserve granulite facies mineral assemblages, locally statically retrogressed to amphibolite facies. They may be a different association from the Fiskenaeset and Godthåbsfjord-Buksefjorden complexes.

Lead isotopic data have been reported for anorthosites on Storø and Ivnuagtoq, inner Godthåbsfjord, by Gancarz (1976) and for anorthosites from Buksefjorden, Faeringehavn, Ameralik, and western Nordlandet by Taylor et al. (1980). The Pb isotopic characteristics of these anorthosites are similar to those of the gneisses that enclose and intrude them (see under Nûk gneisses).

Although the Godthåbsfjord anorthositic rocks do not preserve as many primary features as those in parts of the Fiskenaeset region, they are the next most extensive, varied, and well preserved rocks of this type in the West Greenland Archean. Potentially the best areas for further study are Storø in Godthåbsfjord and the nunataks Akugdlerssuaq (Nutman, 1982) and Nunatarssuk east of the head of Godthåbsfjord. The west Nordlandet leucogabbro complex has been mapped on a scale of 1:20,000 but has not been studied in any detail.

## NÛK GNEISSES

The term Nûk gneisses is used for all quartzofeldspathic gneisses (deformed granitoid intrusives) in the Godthåbsfjord region that do not contain Ameralik dikes and that intrude and migmatize Amitsoq gneisses, Malene supracrustal rocks, and the layered anorthositic complexes (McGregor, 1973). It is now apparent that the Nûk gneisses include at least two distinct and probably unrelated generations of rocks.

### 1. Pre-2900 Ma Gneisses

The type Nûk gneisses, those first mapped by McGregor (1973), crop out on the western parts of the peninsulas between Godthåbsfjord and Ameralik and on islands to the SSW. They extend north through the islands of Sadelø and Bjørneføen. The oldest phases are massive, homogeneous, dioritic gneisses that were subsequently intruded by voluminous, polyphase, tonalitic gneisses. The youngest major phases are granodiorites that form thick, homogeneous sheets and the cores of diapiric domal antiforms as well as the matrix of agmatitic units. Smaller bodies of trondhjemitic gneiss cut the other lithologies. Intrusive relations and primary igneous textures are best preserved on eastern Sadelø,

Bjørnefjorden, and northwestern Storø. To the west and south the type Nûk gneisses were affected by intense ductile deformation in a late, NNE-SSW-trending linear belt.

The best isotopic dates obtained on the type Nûk gneisses are U/Pb zircon concordia intersection dates of 3070 and 3020 Ma on early tonalitic phases from southeastern Bjørnefjorden and of 2980 and 2940 Ma on homogeneous, tonalitic gneisses from Nuuk (Godthåb) town (*Baadsgaard and McGregor, 1981*), and a Rb/Sr whole rock isochron age of  $2980 \pm 50$  Ma ( $Sr_i = 0.7022 \pm 0.0003$ ) on a single, thick unit of massive, granodioritic gneiss on the east coast of Bjørnefjorden (*Taylor et al., 1980*). Other specimens from the type Nûk gneisses in Nuuk town give younger and more discordant zircon ages (*Baadsgaard and McGregor, 1981*) and a Rb/Sr whole rock isochron age of  $2770 \pm 170$  Ma (*Moorbath and Pankhurst, 1976*; recalculated by *Taylor et al., 1980*). These younger ages are considered to reflect disturbance of the isotopic systems, associated with subsequent tectonothermal events.

A U/Pb zircon concordia intercept age of  $2982 \pm 7$  Ma (*Garde et al., 1985*) shows that the Taserssuaq tonalite, northwest of the head of Godthåbsfjord, falls within the age range of the type Nûk gneisses. The Taserssuaq tonalite (originally called the Taserssuaq granodiorite) is a rather homogeneous, but multiphase, weakly foliated intrusion that crops out over an area of more than 1500 km<sup>2</sup>.

A reconnaissance study of the chemistry of the type Nûk gneisses was reported by *McGregor (1979)*, who suggested that the more voluminous phases could be the products of partial melting of metabasaltic rocks such as the Malene amphibolites. Further work on their chemistry is in progress at Leicester University.

The quartzofeldspathic gneisses on the Nordlandet peninsula west of Godthåbsfjord (*Macdonald, 1974; Reed, 1980*) are not included within the Nûk gneisses because their relations to the type Nûk gneisses across the fjord are uncertain. Except for a few late sheets of diorite, granodiorite, and pegmatite, all of the rocks on Nordlandet have or have had granulite facies mineral assemblages. There has been widespread, patchy, static retrogression to amphibolite facies. Supracrustal rocks are much less abundant on southern Nordlandet than in most other parts of the West Greenland Archean and are highly broken up by the gneisses. They become progressively more common and form more continuous units toward the north. No early Archean rocks have been recognized on Nordlandet. The Pb analyzed from Nordlandet gneisses and leucogabbros is not contaminated by a less radiogenic Amitsoq-type component as is Pb in Nûk gneisses and anorthositic rocks that are

intercalated with early Archean rocks (*Taylor et al., 1980*). Granulite facies gneisses and leucogabbros from Nordlandet and from Sukkertoppen, 120 km to the north, have yielded a Pb/Pb whole rock isochron age of  $3000 \pm 70$  Ma (*Taylor et al., op. cit.*). This is taken to date the granulite facies metamorphism but shows that the Nordlandet gneisses are probably about the same age as the type Nûk gneisses.

The earlier and most abundant gneiss phases on southern and western Nordlandet are mainly dioritic in composition. They are strongly veined by leucocratic material that appears to be the product of local anatexis of the diorites. Later gneiss phases are coarse-grained, leucocratic trondhjemites and tonalites and rare granodiorites and granites. They occur as sheets that break up the older rocks into agmatites and as large, massive bodies, in places forming the cores of diapiric domal structures. Their intrusion post-dated deformation of the dioritic gneisses. Minor late plagioclases, composed of 85–90% andesine with hornblende and biotite, are closely associated with basic lithologies, of which they may be anatectic products.

## 2. Post-2800 Ma Gneisses

Dykes of younger trondhjemitic and granitic gneiss within the type Nûk gneisses are termed Qârusuk dikes (*McGregor et al., 1983*). One such dike on southeastern Bjørnefjorden has yielded a U/Pb zircon concordia intercept age of 2660 Ma (*Baadsgaard and McGregor, 1981*). Granodioritic to granitic gneisses of similar age are more extensive in inner Godthåbsfjord (*Coe and Robertson, 1982; Robertson, 1983; Brewer et al., 1984*). Major, mappable units of late Archean granodioritic gneiss south of Ameralik may also belong to this group. At present the distribution of this group of gneisses is uncertain. The age determinations available are mainly in the range of 2600–2700 Ma.

It is now apparent that earlier collections of rocks that have been used for isotopic studies of Nûk gneisses (*Moorbath and Pankhurst, 1976*; and some of the suites considered by *Taylor et al., 1980, 1984*) are mixed suites that include some post-2800 Ma gneisses. The collections from the Buksefjorden map sheet area comprise older Nûk phases, post-2800 Ma gneisses, and probably also some Amitsoq gneisses that were affected by late Archean granulite facies metamorphism and subsequent retrogression (see below). Consequently, some of the conclusions reached in these studies can no longer be accepted at face value.

*Taylor et al. (1980)* found that Pb in Nûk gneisses and anorthosites, within the part of the region where early Archean rocks have been recognized, contain

variable proportions of anomalously unradiogenic Pb that they interpreted as derived from early Archean, Amitsoq gneiss-type continental crust. The samples with the highest proportions of Amitsoq-type Pb are probably all from the younger (2700–2600 Ma) gneisses. Sm/Nd analyses reported by *Taylor et al.* (1984) indicate a contribution of Nd from low-Sm/Nd crustal sources for some of the same samples that show contamination with Amitsoq-type Pb. Most of the samples used in this study are from the post-2800 Ma gneisses. The Pb and Nd, together with other chemical characteristics (*McGregor et al.*, 1983) of these rocks indicate an origin by partial melting of sialic crustal rocks that included a substantial early Archean component. High, variable alkali contents and very variable trace element chemistry in the Qârusuk dikes suggest they crystallized in a fluid-rich environment and therefore their chemistry must be regarded as controlled by both igneous and hydrothermal processes.

Many of the Nûk gneisses for which *Compton* (1978) reported REE concentrations belong to the post-2800 Ma group. Older gneisses studied by *Compton* are all from the terrain affected by 2800 Ma granulite facies metamorphism (see below), where Sm/Nd systematics appear to have been upset during the granulite facies metamorphism. *Compton's* data cannot, therefore, be used to discuss the origin of the more voluminous, pre-2900 Ma type Nûk gneisses.

Mid to late Archean gneisses like the Nûk gneisses are by far the most abundant rocks in the West Greenland Archean. They occur mainly as folded sheets that split up sequences of mid-Archean supracrustal and anorthositic rocks and, in the Godthåbsfjord region, also early Archean rocks. The great lateral extent and concordant form of the gneiss sheets is in part the result of extreme attenuation by deformation, but is in part also a primary feature. It appears that the Nûk-type magmas were commonly intruded as sheets along active thrust planes between and within units of older rocks and that differential movement of the walls of the sill as the magmas solidified caused many of them to crystallize with gneissic textures (*McGregor*, 1979; *Myers*, 1978, 1985a,b).

## MID-ARCHEAN CRUSTAL STRUCTURE

The following model is suggested by V.R.M. as a possible explanation of many features of the central part of the West Greenland Archean: Mid-Archean oceanic crust made up of basic volcanics with subordinate anorthositic cumulate complexes and locally derived sediments was carried toward a continental mass of early Archean rocks beneath which it descended in some form

of subduction zone. Detrital sediments derived from the early Archean rocks and from contemporaneous, subduction-related intermediate to acidic volcanics were deposited on the basic volcanics as they approached the continental margin. Slices of the composite supracrustal sequence were intercalated tectonically with the early Archean rocks in the deeper parts of the continent, while mainly basic rocks were flaked off and underplated the continent (*Weaver et al.*, 1982). Dioritic, tonalitic, and granodioritic magmas generated by partial melting associated with subduction and were emplaced along active thrusts mainly in the deeper parts of the pile. There was a tendency for denser, more mafic magmas to accumulate at deeper levels.

According to this model, differences from area to area in the proportions of the early and mid-Archean lithological associations could be explained in terms of different crustal levels:

1. The shallowest level now exposed is in the Isukasia area, which is made up entirely of early Archean rocks. Mid-Archean supracrustal and intrusive rocks are absent.

2. A deeper level is preserved in the tract through Godthåbsfjord where mid-Archean (Malene) supracrustal and anorthositic rocks are intercalated with early Archean rocks. Mid-Archean (type Nûk) intrusives comprise subequal amounts of tonalitic and granodioritic compositions.

3. Much of the Fiskensæset region and northern Nordlandet represent a deeper level still, interpreted in this model as below the base of the early Archean continent. The oldest rocks are mid-Archean basic supracrustal rocks with oceanic affinities and anorthositic cumulates. These are subordinate in volume to mid-Archean intrusives.

4. The deepest level now exposed is on southern Nordlandet. Early Archean rocks are absent and there are only minor amounts of mid-Archean supracrustal rocks derived almost exclusively from basic volcanics. The dominant rocks are mid-Archean leucogabbroic to dioritic intrusives together with trondhjemitic rocks formed by partial melting of the diorites under granulite facies conditions.

The overall structure of the Fiskensæset region may be that of a very large dome centered south of eastern Sermilik (see the 1:500,000 map sheet). The form of the inferred dome has been strongly modified by late Archean folding. In this interpretation, rocks from the deepest exposed crustal level, in which the Ilivertalik granite suite is a major component, crop out in the center of the dome. Early Archean rocks occur only at higher crustal levels on the flanks of the inferred dome to the

north in the Godthåbsfjord-Faeringehavn region and to the south in the Frederikshåb-Ivigut region (*Taylor and Kalsbeek*, this volume).

Nordlandet is interpreted as a tilted block with rocks from progressively deeper crustal levels exposed along a section from north to south.

## LATE ARCHEAN PLUTONIC DEVELOPMENT

Between 3000 and 2500 Ma the region was affected by a complex and as yet rather imperfectly understood sequence of deformation, metamorphism, generation, and intrusion of granitoid magmas and movement of especially minor and trace elements.

### 1. Deformation

The deformational history of much of the region has not been considered in detail. The best studied areas are the Isukasia area (*Nutman and Rosing*, this volume), the Ivisartoq area (*Hall and Friend*, 1979; *Chadwick*, 1985) and the peninsula and islands southwest of the mouth of Ameralik (*Chadwick and Nutman*, 1979). *Chadwick and Coe* (1983) summarized ideas on the structure within the Buksefjorden 1:100,000 map sheet.

A strong, subhorizontal, planar fabric was probably developed widely in the mid-Archean, associated with thrusting that interleaved early Archean rocks with Malene supracrustal rocks and controlled the intrusion of some Nûk gneiss parents.

In most areas where there are good lithological markers, early recumbent isoclinal folds can be identified and are refolded by one or more generations of upright structures. However, fold phases or sequences of phases with similar styles were not necessarily synchronous from area to area. For example, in the area north of Fiskenaeset large-scale recumbent folds were refolded by two sets of folds with steep axial surfaces at high angles to one another (*Myers*, 1978, 1985b). All three phases *pre-date* granulite facies metamorphism at ca. 2800 Ma (see below). Between Ameralik and the head of Buksefjorden a major recumbent fold, the Inugssugsuaq nappe, that is refolded by large upright folds (*Chadwick et al.*, 1982) is interpreted by us as *post-dating* late Archean granulite facies metamorphism.

Late ductile deformation was concentrated in linear belts, some of which are indicated in Figure 1. One such belt passes through the peninsula on which Nuuk town is situated and separates the granulite facies rocks of Nordlandet from rocks to the east that never reached granulite facies. The rocks in this belt have a strong, subvertical, planar fabric element parallel to the orientation of the belt as a whole and a strong linear

fabric element that plunges in most places at moderate angles to SSW. Toward the south the deformation zone broadens and the planar fabric element becomes less pervasive, although the linear fabric element remains strong. South of the mouth of Ameralik the linear fabric is coaxial with sheath folds that have the form of flattened dunes' caps (*Chadwick and Nutman*, 1979). Structures in the linear belt are consistent with a sinistral strike-slip component of displacement across the belt and a vertical component that brought up the rocks of Nordlandet with respect to those east of the belt.

It is important to realize that most of the rocks in the West Greenland Archean have been affected by one or more episodes of intense ductile deformation that rotated earlier structures into parallelism and streaked out bodies of different lithologies. This produced regularly layered rocks (gneisses, amphibolites, meta-anorthosites, etc.) from parents that may not have been layered at all. *Myers* (1978) has figured particularly clear examples of this process.

### 2. Metamorphism

The belt of rocks that crops out from Faeringehavn through much of Godthåbsfjord to the margin of the Inland Ice in the Isukasia area (Figure 1) and that contains all the rocks that have yielded early Archean isotopic ages differs from the remainder of the northern part of the West Greenland Archean in that it did not reach granulite facies in the late Archean.

Granulite facies metamorphism northwest of this belt appears to have occurred 3000–2950 Ma ago, about the same time as intrusion of the very voluminous Tasersuaq tonalite (see above under Nûk gneisses). Conditions of 800°–850°C and 7–9 kb total pressure have been calculated for granulite facies rocks on southern Nordlandet (*Reed*, 1980) and 825°C and 8.3 kb for rocks a little north of Nordlandet (*Dymek*, 1984).

South and southeast of the Godthåbsfjord region there are areas with granulite facies mineral assemblages separated by areas with amphibolite facies assemblages (see the 1:500,000 geological map and Figure 1). The age of the granulite facies metamorphism around Fiskenaeset is given by: (a) A Pb/Pb whole rock isochron age of  $2810 \pm 70$  Ma for four anorthositic rocks and one gneiss (*Black et al.*, 1973). (b) An essentially concordant age of 2790 Ma for a large euhedral zircon from an ultramafic pod. This zircon is considered to have crystallized during granulite facies metamorphism (*Pidgeon and Kalsbeek*, 1978). (c) A concordia intercept age of  $2795^{+11}_{-7}$  Ma on zircons from the Ilivertalik granite, considered to have been emplaced during granulite facies metamorphism (*Pidgeon et al.*,



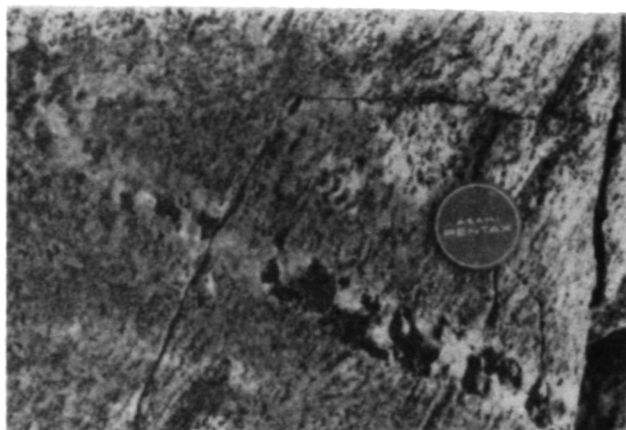


Fig. 2. Big-hornblende pegmatite in retrogressed gneisses with blebby texture, Kangimut sangmissoq, Ameralik.

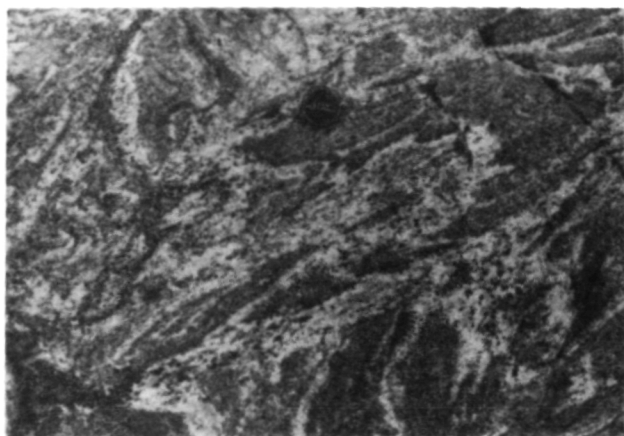


Fig. 3. Pegmatitic patches in mafic gneisses retrogressed from granulite facies, Amitsorssuaq, Buksefjorden.

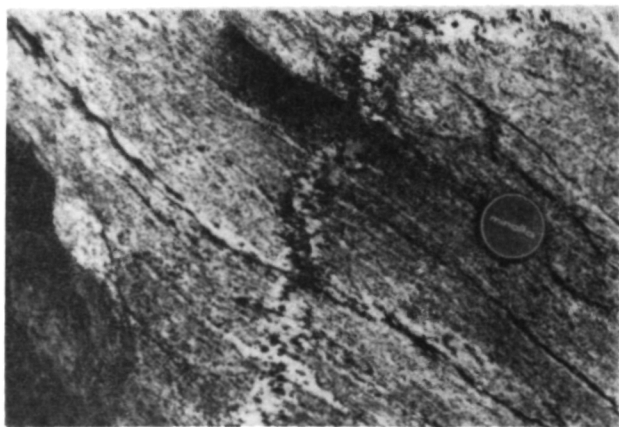


Fig. 4. Slightly deformed big-hornblende pegmatite in gneisses retrogressed from granulite facies, north coast of Buksefjorden.

1976). Granulite facies metamorphism thus appears to be 150–200 Ma later here than northwest of Godthåbsfjord.

Some workers have assumed that the present granulite-amphibolite facies boundaries in the Fiskanaeset and Sermilik-Buksefjorden areas are close to the original prograde boundaries and that granulite facies metamorphism outlasted all major ductile deformation (Wells, 1976, 1979; Myers, 1976, 1978; Chadwick and Coe, 1984). Our own observations indicate that most of the amphibolite facies rocks between Fiskanaeset and a line that extends NNE through Kangerdluarsoruseq (Faeringehavn) and central Ameralik (Figure 1) originally had granulite facies assemblages but have been retrogressed. Retrogression was associated in many places with deformation and, at least in the north, with intrusion of the younger (post-2800 Ma) suite of Nûk gneisses.

Our conclusions are based on recognition of textural features related to crystallization of orthopyroxene that are preserved in relic form in rocks that have been retrogressed to amphibolite facies:

(a) Concentration of mafic minerals in gneisses of intermediate composition into open clusters, giving the rocks a characteristic "blebby" texture (Figure 2). Where retrogression was incomplete, the mafic clusters are seen to be secondary after orthopyroxene or garnet. Diffusely bounded pegmatitic patches were developed that in retrogressed gneisses have prominent, well-separated mafic clots or large hornblende grains (Figure 3).

(b) Blurring of earlier structures in gneisses (for example, original sharp contacts between intrusive phases) produced nebulitic texture. Because of this process of textural homogenization it is not usually possible to separate components of different ages in quartzofeldspathic rocks that have been affected by granulite facies metamorphism.

(c) Occurrence, especially in intermediate gneisses, of discordant pegmatites with prominent large hornblendes (Figures 2 and 4). In places, the hornblendes can be seen to be secondary after orthopyroxene. The thinner big-hornblende pegmatites appear simply to be planar zones in which the gneisses were recrystallized to very large grain sizes.

(d) Abundant mafic-rich pegmatitic patches and veins in basic lithologies (Figures 5, 6). These contrast with the typically very leucocratic pegmatitic segregations formed in basic rocks under high amphibolite facies conditions (Figure 7). In places, however, mafic pegmatitic segregations with clinopyroxene or garnet formed under amphibolite facies conditions.

(e) Small, replacive ultramafic veins and patches made up of orthopyroxene in unretrogressed areas and

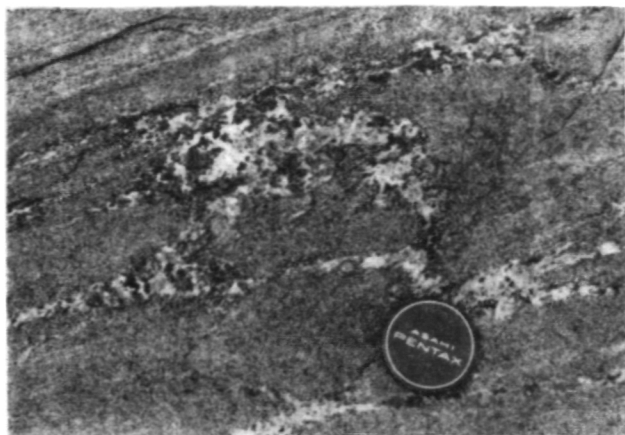


Fig. 5. Mafic segregation pegmatites with orthopyroxene in pyribole (granulite facies mafic rock), Tovqussap nunâ.

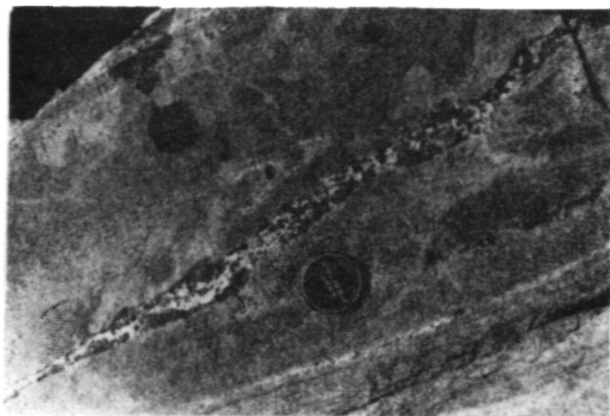


Fig. 6. Mafic pegmatite vein with orthopyroxene in pyribole, Tovqussap nunâ.

hornblende in retrogressed areas are common in basic lithologies (Figure 8).

Some or all of these features are found in rocks that were partly or completely retrogressed from granulite facies under static conditions. We have been able to follow these clearly retrogressed rocks into areas where relic granulite facies textural features have been progressively modified and, finally, completely destroyed by deformation with the formation of a new foliation.

The original prograde boundary (Figure 1) between rocks affected by the 2800 Ma granulite facies metamorphism and those to the northwest in the belt through Godthåbsfjord that were not metamorphosed above amphibolite facies in the late Archean has been obscured by retrogression, intrusion of the later suite of Nûk gneisses and the Qôrquut granite complex (see below), major folding, and strong deformation in the late linear belts.



Fig. 7. Leucocratic, amphibolite-facies, segregation pegmatite in amphibolite (Ameralik dike), Præstefjord.

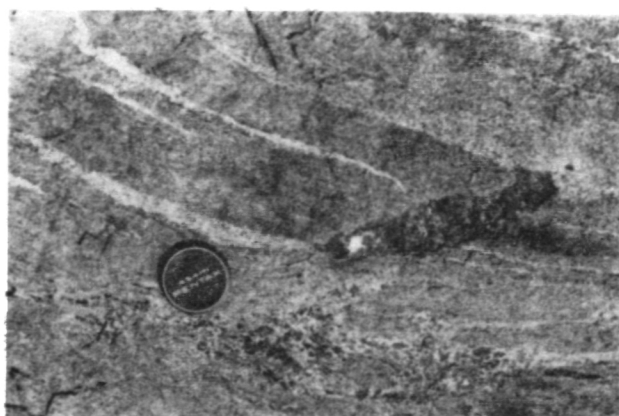


Fig. 8. Replacive orthopyroxene patch in pyribole, Tovqussap nunâ.

Dymek (1978, 1984) discussed the polyphase metamorphism of the Malene supracrustal rocks. The earliest and highest grade of metamorphism for which petrographic evidence is preserved at any locality ranges from middle amphibolite grade in a zone through western Godthåbsfjord that includes Sadelø and Bjørneøen to hornblende granulite grade on Nordlandet and north of the mouth of Fiskefjord. Metamorphism occurred almost entirely within the sillimanite stability field. However, the highest grade assemblages date from different episodes of metamorphism in different places: early granulite facies metamorphism at 3000–2950 Ma northwest of Godthåbsfjord; amphibolite facies metamorphism at ca. 2800 Ma in parts of the belt through Godthåbsfjord; and metamorphism at 2700–2600 Ma in areas where there was complete recrystallization associated with late deformation, for example, in the linear belt through Nuuk town.

In many places there is petrographic evidence of retrograde metamorphism under conditions where kyanite was stable and that Dymek interpreted as the result of renewed crustal heating and hydration.

Amîtsoq gneisses around and south of the mouth of Ameralik show considerable isotopic evidence of metamorphic crystallization in the period 2700–2500 Ma. This is seen in K/Ar and  $^{40}\text{Ar}/^{39}\text{Ar}$  dates on hornblende (Pankhurst *et al.*, 1973); U/Th/Pb dates on sphene, apatite, and allanite, Rb/Sr relations in hornblende, K-feldspar, apatite, allanite, and sphene (Baadsgaard *et al.*, 1976); and by leachable Pb in feldspars that is considered to come from U-rich inclusions (Gancarz and Wasserburg, 1977). Limited open system behavior is indicated by considerable scatter of points on the Pb/Pb whole rock errorchron (MSWD = 21) and by specimens of mainly basic rocks that scatter about a 2700 Ma Rb/Sr reference isochron (Black *et al.*, 1971). The lower intercept with the concordia of the Akilia zircon chord suggests Pb loss during metamorphism at ca. 2500 Ma (Baadsgaard *et al.*, 1984).

Mineral-chemical studies suggest depths of burial of 15–30 km for rocks now exposed and indicate thick continental crust in the late Archean (Wells, 1979; Dymek, 1984).

### 3. Element Mobility

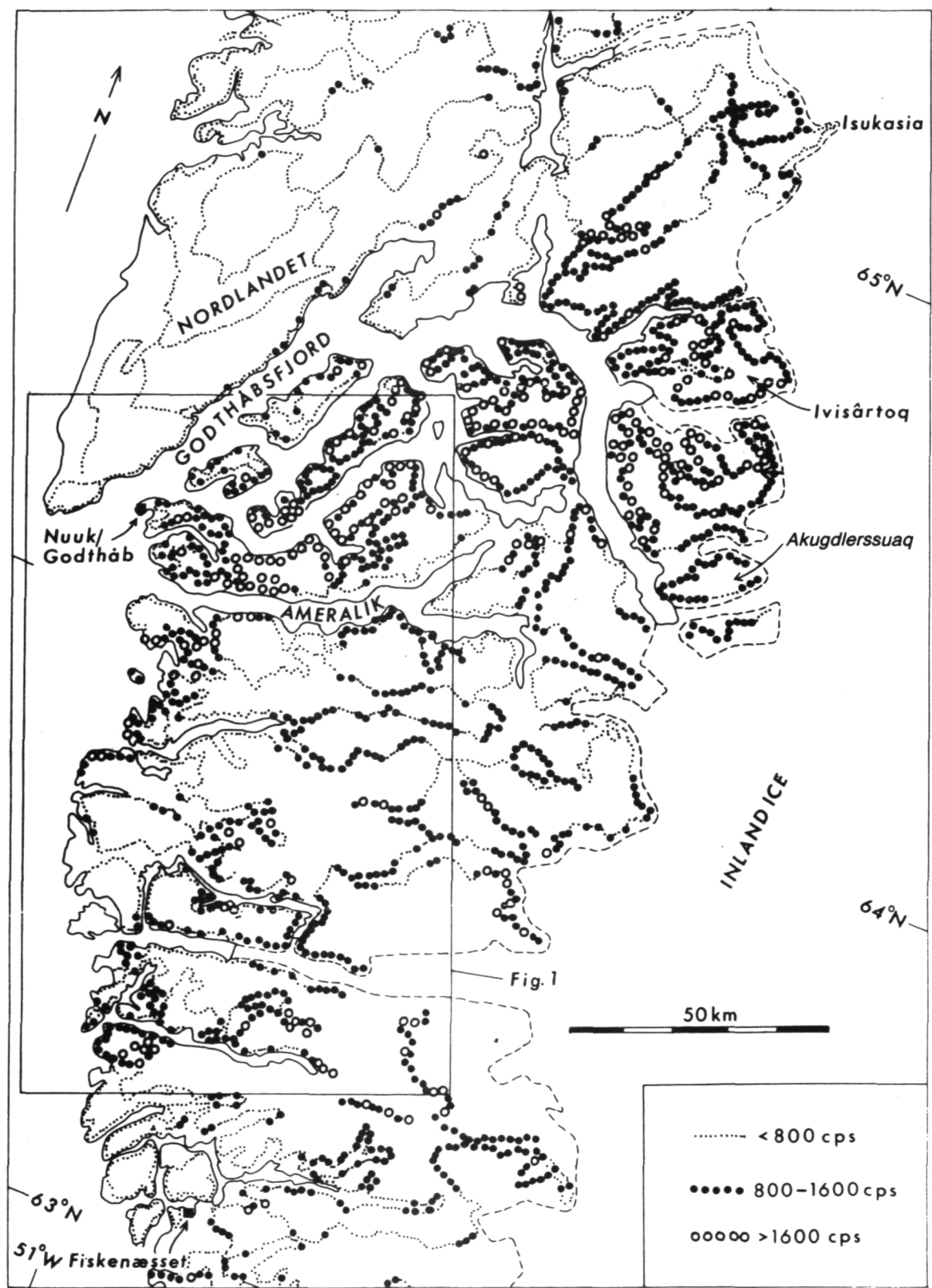
In common with many other granulite facies terrains, the rocks affected by late Archean granulite facies metamorphism in southern West Greenland are strongly impoverished in U, Th, Rb, and K (Kalsbeek, 1974, 1976). The airborne radiometric survey (Secher, 1976, 1977; Secher and Steenfelt, 1981) shows low levels of radioactivity, reflecting low contents of K, U, and Th, in areas where granulite facies mineral assemblages are still extensively preserved on Nordlandet and in the area north of Fiskenaæsset (Figure 9). A belt with very low radioactivity extends NNE from the mouth of Sermilik through Buksefjorden to and beyond the middle of Ameralik. Most of the rocks in this belt now have amphibolite facies mineral assemblages, but there is widespread field evidence that they have been retrogressed from granulite facies. The western margin of the low radioactivity belt corresponds to the position of the prograde granulite-amphibolite facies boundary indicated by field evidence. Areas with higher radioactivity to the southeast correspond at least in part to outcrops of more potassic rocks including the Ilivertalik granite (see below). The airborne radioactivity survey shows a belt with unusually high radioactivity immediately west of the original prograde granulite-

amphibolite facies boundary, i.e., on the amphibolite facies side and presumably structurally just above rocks affected by granulite facies metamorphism. In part, the high radioactivity reflects the outcrop of the Qôrqt granite complex (see below) and other late granitic rocks, but Amîtsoq gneisses within the belt and, in inner Godthåbsfjord, Nûk gneisses also have high levels of radioactivity. The high radioactivity belt is relatively narrow south of Ameralik, but widens to the northeast. This may in part be the result of late deformation, with attenuation of the belt in linear deformation zones to the south and repetition by folding to the northeast.

The high radioactivity belt appears to be a zone of accumulation of elements including K, U, Th, Rb, and Pb that were expelled from deeper rocks affected by 2800 Ma granulite facies metamorphism. Amîtsoq and Nûk gneisses within the belt in inner Godthåbsfjord are enriched in K, Rb, and Pb compared with their equivalents outside the belt, and Sr and Pb isotopes indicate that this enrichment could not have occurred much earlier than 2800 Ma (S. Robertson, personal communication). The enriched zone was probably the source region of granites formed by partial melting (? associated with renewed heating and influx of aqueous fluids) during the period 2700–2500 Ma. The largest volumes of late granites, e.g., the “main body” of the Qôrqt granite complex (see below), may have been generated where the enriched zone had been thickened as a result of folding.

Rb/Sr, Pb/Pb, and systems appear to have been highly disturbed by the 2800 Ma granulite facies metamorphism south of Godthåbsfjord. This is seen most clearly in specimens from a unit of what we confidently interpret as early Archean Amîtsoq gneisses that crops out on the south coast of Ameralik between Kangimut sangmissoq and Qasignánguit (Figure 1; see locality 3.3. in the Excursion Guide). Specimens from this unit that we consider must include a large proportion of Amîtsoq gneisses yield a Rb/Sr whole rock isochron age of  $2270 \pm 180$  Ma with  $\text{Sr}_i = 0.7019 \pm 0.00005$  and a Sm/Nd model age of ca. 2800 Ma. The pattern of Pb isotopes in the samples is analagous to the pattern in the type Nûk gneisses, with between 1% and 33% of an Amîtsoq-type component in the Pb in 16 samples and about 49% in 2 samples (Jones *et al.*, this volume; Collerson *et al.*, this volume).

The obvious differences between the type Amîtsoq gneisses in outer Ameralik and the gneisses at Kangimut sangmissoq-Qasignánguit are the following: (a) The latter were recrystallized during the late Archean under granulite facies conditions and subsequently retrogressed to amphibolite facies, while the type Amîtsoq gneisses were not metamorphosed above amphibolite facies in the same period. (b) The Kangimut sangmissoq-





Qasigiánguit unit of Amítoq gneisses is enclosed in and probably to some extent also penetrated by Nûk gneisses. The type Amítoq gneisses in outer Ameralik lie within a 1600 km<sup>2</sup> tract of early Archean rocks interrupted only by thin units of Malene supracrustal rocks. Nûk gneisses penetrate the margin of this tract, but occur only very locally within it.

The type Amítoq gneisses retain early Archean Rb/Sr, Pb/Pb, and Sm/Nd (K. D. Collerson, personal communication) whole rock systematics. We conclude that resetting of these systems in the gneisses at Kangimut sangmissoq-Qasigiánguit is the result of processes associated with granulite facies metamorphism and subsequent retrogression. Proximity of Nûk gneisses may also have been a contributing factor.

*Kalsbeek and Pidgeon* (1980) considered Rb/Sr isotope systematics of gneisses of Nûk type in the Fiskenæsset region for which zircon U/Pb results suggest ages of at least 2900 Ma. They found that the isotopic characters could be explained if the rocks had suffered large-scale Sr isotope homogenization after their emplacement, probably at ca. 2800 Ma, and small-scale isotope homogenization during later metamorphism.

*Grant and Hickman* (1984) pointed out the lack of Sr isotopic evidence for a history prior to 2800 Ma in gneisses from the terrain affected by late Archean granulite facies metamorphism south of Godthåbsfjord and from what we interpret as the enriched zone in inner Godthåbsfjord. They concluded that if the Nûk-type gneisses in this terrain were broadly cogenetic with the type Nûk gneisses that escaped granulite facies metamorphism, then addition of Rb, loss of Sr, and lowering of <sup>87</sup>Sr/<sup>86</sup>Sr ratios through complete isotopic equilibrium with a reservoir containing unradiogenic Sr were all required to account for the isotopic differences.

### CAUSE OF LATE ARCHEAN GRANULITE FACIES METAMORPHISM

*Kalsbeek* (1976) suggested that the depletion in U, Th, and Rb observed in granulite facies rocks in the northern part of the Fiskenæsset region might be the result of partial melting that produced granites such as the Ilivertalik granite complex and left a residue of hypersthene gneisses. The Ilivertalik granite complex crops out very extensively as thick folded sheets of homogeneous augen gneiss in the center of the terrain affected by 2800 Ma granulite facies metamorphism (*Kalsbeek and Myers*, 1973; *Myers*, 1976. See the

1:500,000 geological map sheet). It is interpreted as intruded during granulite facies metamorphism (*Pidgeon et al.*, 1976). The parent lithology was granite with large potash feldspar megacrysts associated with smaller amounts of layered tonalite and diorite. *Wells* (1979) concluded that the chemistry of the granulite facies gneisses north of Sermilik did not support *Kalsbeek's* hypothesis. Field evidence does not indicate extensive partial melting and segregation of granitic melts at the present level of exposure during granulite facies metamorphism. The disruption of older lithologic units was not associated with granulite facies metamorphism, but with intrusion of the parents of the Nûk gneisses and equivalent rocks.

*Wells* (1979) suggested that granulite facies metamorphism in the Buksefjorden area was the result of heat transferred to the crust by intrusion of the Nûk magmas. This view was based on acceptance at face value of *Moorbath and Pankhurst's* (1976) whole rock isochron ages of between 3000 and 2750 Ma for rocks collected as Nûk gneisses. It is now apparent that these dates reflect metamorphic or metasomatic processes rather than the intrusion of the Nûk parent magmas. Dates from outside the terrain affected by granulite facies metamorphism (the type Nûk gneisses in western Godthåbsfjord and gneisses in the southern part of the Fiskenæsset region; *Pidgeon and Hopgood*, 1975; *Pidgeon and Kalsbeek*, 1978) indicate that the parents of the bulk of the gneisses in this part of the West Greenland Archean were intruded before 2950 Ma. However, isotopic data show that granulite facies metamorphism in the Fiskenæsset region occurred at, or at least continued until ca. 2800 Ma. It is clear from *Wells's* (1980) calculations that heat transported to the crust by Nûk-type magmas before 2950 Ma would have been lost by conduction before 2800 Ma.

The mechanism suggested by *Wells* does not seem appropriate for the granulite facies metamorphism south of Godthåbsfjord, but it may possibly explain the granulite facies metamorphism northwest of Godthåbsfjord, which present data suggest occurred shortly after or at the same time as the intrusion of later phases of the type Nûk gneisses and the Tasersuaq tonalite. Some differences between granulite facies metamorphism on either side of Godthåbsfjord are summarized in Table 1.

A possible model for the 2800 Ma granulite facies metamorphism south of Godthåbsfjord is that it was caused by an influx of heat and fluids from the mantle,

Fig. 9. Radiometric map of the Godthåbsfjord region and the northern part of the Fiskennæsset region, based on airborne gamma-spectrometric survey from *Secher and Steenfelt* (1981). Values in counts per second.

Table 1. Comparison of late Archean granulite facies metamorphism northwest and south of Godthåbsfjord

NW of Godthåbsfjord (Nordlandet-Qugssuk)	S of Godthåbsfjord (Buksefjorden-Sermilik-Fiskenæsset)
Age: 3000–2950 Ma	Age: ca. 2800 Ma
"Blebbly" gneisses, big-hornblende pegmatites rare or absent	Extensive textural modification produced "blebby" and nebulitic textures in gneisses and (retrogressed) big-hornblende pegmatites
Extensive partial melting under granulite facies conditions	Limited partial melting under granulite facies conditions
No rapakivi-type granites	Associated with intrusion of rapakivi-type Ilivertalik granite suite
No high radioactivity belt along original prograde boundary to the east in Qugssuk	High radioactivity belt enriched in K, U, Th, Rb, Pb along original prograde boundary to the northwest

possibly through intrusion of basic magma near the base of the crust. The Ilivertalik granite complex could be the product of melting of deep crustal rocks by a mechanism like that proposed for the Amitsoq iron-rich suite (Nutman *et al.*, 1984), with which it has chemical similarities. Fluids migrating upwards through the crust could have caused extensive recrystallization to orthopyroxene-bearing assemblages with the textural features noted above. They could be the agents that moved U, Th, K, Rb, and Pb out of the rocks that developed granulite facies assemblages and into the enriched zone above the prograde granulite-amphibolite facies boundary. They could be the cause of movement of Sr and fractionation of the REE. Rb, Pb, U, and the light REE may have been reintroduced during subsequent retrogression (Bridgwater *et al.*, 1985).

### QÔRQUT GRANITE COMPLEX

Late, essentially post-tectonic granites crop out within a belt that extends from the mouth of Buksefjorden NNE through Qôrqt and Ũmánap suvdlua into inner Godthåbsfjord. These rocks are now termed the Qôrqt granite complex (Brown and Friend, 1980; Brown *et al.*, 1981), having originally been called the Qôrqt granite (McGregor, 1973). The largest area of continuous outcrops of granite (referred to as the "main body" of the complex) lies between Ameralik and Kapisigdlit kangerdlua (Figure 10) and is made up of a very large number of discrete sheets with abundant enclaves and rafts of country rocks (Figure 11).

Samples from the northern part of the "main body" yield a U/Pb zircon concordia intercept age of 2530

± 30 Ma (Baadsgaard, 1976). Moorbath *et al.* (1981) reported Rb/Sr and Pb/Pb isotopic data on a varied suite of Qôrqt granites from localities over a distance of 28 km from Ameralik to Sulugssugutip kangerdlua. Twenty-three whole rock samples yield a Rb/Sr errorchron (MSWD = 3.2) age of  $2530 \pm 30$  Ma, with a high  $Sr_i$  value of  $0.7081 \pm 0.0008$ , and a Pb/Pb errorchron (MWSD = 3.2) age of  $2580 \pm 80$  Ma with an apparent  $\mu_1$  value of 6.2. For an assumed mean emplacement age of 2550 Ma, four of the samples yield  $\epsilon_{Nd}$  values in the range of -6.7 to -8.1 with  $T_{CHUR}$  model ages of ca. 3000–3100 Ma (Taylor *et al.*, 1984). The isotopic systematics are consistent with an origin by anatexis of mixed sialic crustal rocks that had generally high Rb/Sr ratios and that included a considerable proportion of U-depleted, early Archean gneisses.

The Qôrqt granite complex between Qôrqt and Sulugssugutip kangerdlua is described by Friend *et al.* (1985). The chemistry and petrogenesis of the granites in this area have been studied by Perkins (1984), whose data and conclusions are reported below. Further work on the overall form and internal structure of the "main body" is in progress at Oxford Polytechnic (Davies, in preparation).

The "main body" of the complex is made up mainly of hypidomorphic granular, nonporphyritic granites with very subordinate granodiorites. The granites have been divided into three groups on the basis of field and petrographic characteristics:

Group 1: leucocratic granites, often containing biotite schlieren and lamellae.

Group 2: grey granites, essentially homogeneous biotite granites.

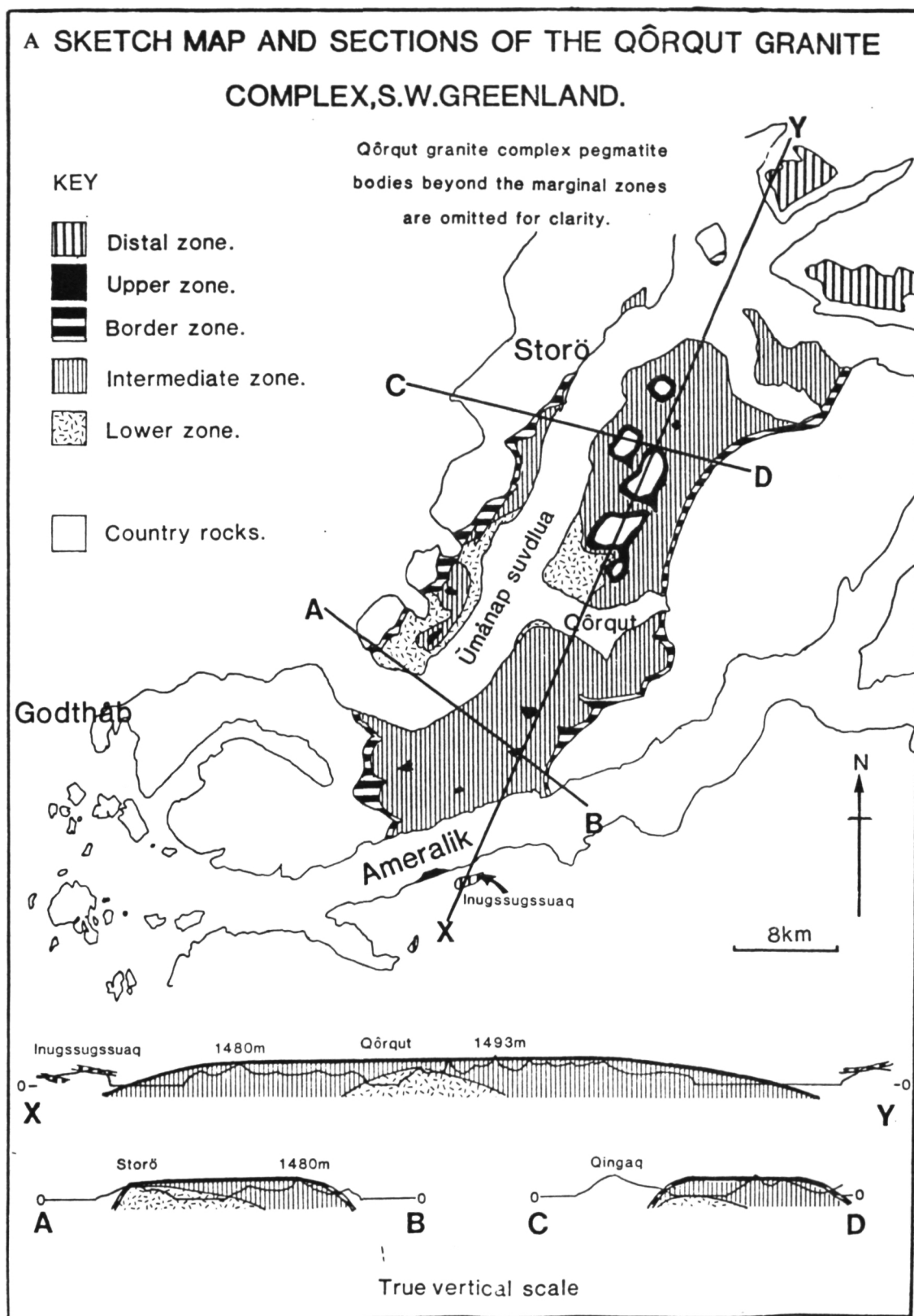


Fig. 10. Sketchmap (a) and sections (b) of the Qôrqut granite complex. (Continued next page.)

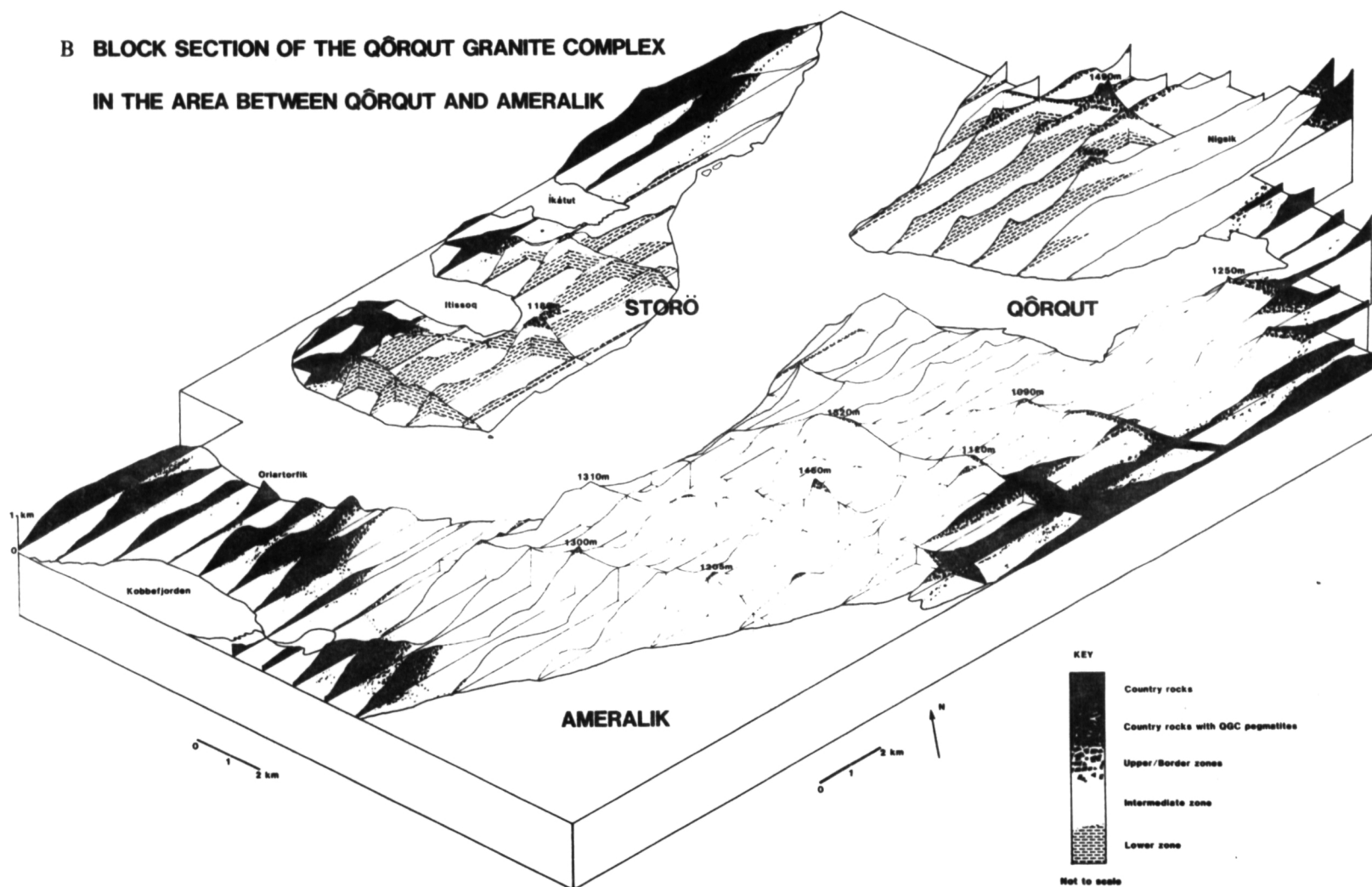


Fig. 10b (continued)

Group 3: composite granites, comprising granite with pegmatite and composite aplogranite-granite pegmatite.

Based on the distribution of these granite types and the included country rock enclaves, the "main body" has been divided into five zones, the characteristics of which are summarized in Table 2 and their distribution shown in Figure 10.

The lower zone is dominated by group 1 inhomogeneous granites which are the earliest phases in the complex. At the western end of Qôrqt the leucocratic granites contain enclaves of Amîtsoq and Nûk gneisses that have been modified by anatexis. There is a range of metatexites and diatexites (Figures 12, 13) in these modified enclaves.

Much of the inhomogeneity and schlieric nature of the leucocratic granites is due to the break-up of the metatexites and the formation of inhomogeneous diatexites. Much of the biotite in the granites appears to be derived from biotite ( $\pm$  plagioclase) melanosomes. The chemistry of the granites is consistent with their being mixtures of nonminimum melts and biotite-rich restites. The leucocratic granites have the characteristics of cotectic melts in equilibrium with quartz, plagioclase, and K-feldspar from an environment where  $P_{H_2O}$  approached  $P_{total}$ . Thus the upward movement of these granites was restricted by the negative slope of the granite solidus.

Grey granites predominate in the intermediate zone and the gneiss enclaves they contain have not been modified by anatexis. They are interpreted to have moved some distance above their zone of generation and to have become more homogeneous. Most of the chemical variation, including that of the REE (Figure 14), in the group 1 and 2 granites could have been produced by batch melting of a mixture of crustal gneisses in which biotite was the major ferro-magnesian phase and melted incongruently. Melting models cannot produce the high Rb values unless the source rocks were enriched in Rb. The field, petrographic, and REE evidence suggests crystallization of the group 3 composite granites from  $H_2O$ -rich fluids.

All the granites analyzed plot within the projection of the 685°C isotherm in the granite system at  $P_{H_2O} = P_{total} = 5$  kbar (Figure 15), the lowest pressure for which comprehensive data is available (Winkler, 1979). By lowering  $P_{H_2O}$  to around 3 kbar, complete agreement with the petrographic data could be obtained.

The field, petrographic, chemical, and isotopic evidence thus all support an origin for the granites of the "main body" by partial melting of a mixture of Amîtsoq and Nûk gneisses within the enriched zone above the late Archean prograde granulite-amphibolite



Fig. 11. Vertical section through about 2000 m of the Qôrqt granite complex in the vicinity of Sagdlia. The upper zone is drawn from photographs of the 1493 m mountain, the intermediate zone from the mountains north of the Qôrqt hotel and the lower zone from Ujarâ.

boundary. The MSWD of 3.2 for the Rb/Sr errorchron reported by Moorbath *et al.* (1981) indicates a high degree of homogeneity of  $Sr_i$  over a distance of 28 km in the "main body" granites at the time of their emplacement. This is surprising considering that the proportion of Amîtsoq to Nûk gneisses in the source region probably varied considerably over the distance

Table 2. Summary of the characteristics of the five zones of the Qôrqut granite complex

Lower zone:	Comprised of dominantly leucocratic granite that contains modified enclaves and some unmodified rafts of country rock all cut by sheets of biotite granite and recut by a few sheets of composite granite.
Intermediate zone:	Comprised of dominantly grey biotite granite of various types that occur as cross-cutting sheets, some of which include subordinate amounts of country rocks and with occasional horizons dominated by country rocks, all of which are cut by composite granites, which are more common than in the lower zone.
Upper zone:	Comprised largely of country rocks as angular rafts enclosed within a network dominantly of sheets of grey biotite granite, the whole forming the host for numerous anastomosing sheets of composite granite that breaks up this host into lozenge-shaped blocks.
Border zone:	Comprised largely of angular blocks of country rocks enclosed within a network of leucocratic granites all of which may be cut by sheets of grey biotite granites.
Distal zone:	Occurring mainly at the NE and SE extremities of the complex and comprising sheets of composite granite and pegmatite cutting country rocks.



Fig. 12. Gneissose melanosome (lower right) giving way to banded metatexite comprising melanosome of biotite-rich layers and leucosome of felsic material.



Fig. 13. Detail of the components of a metatexite showing the hypidiomorphic granular texture of the felsic layers and the biotite-rich melanosome. Note that while there is a prominent banding, the texture is not gneissic.



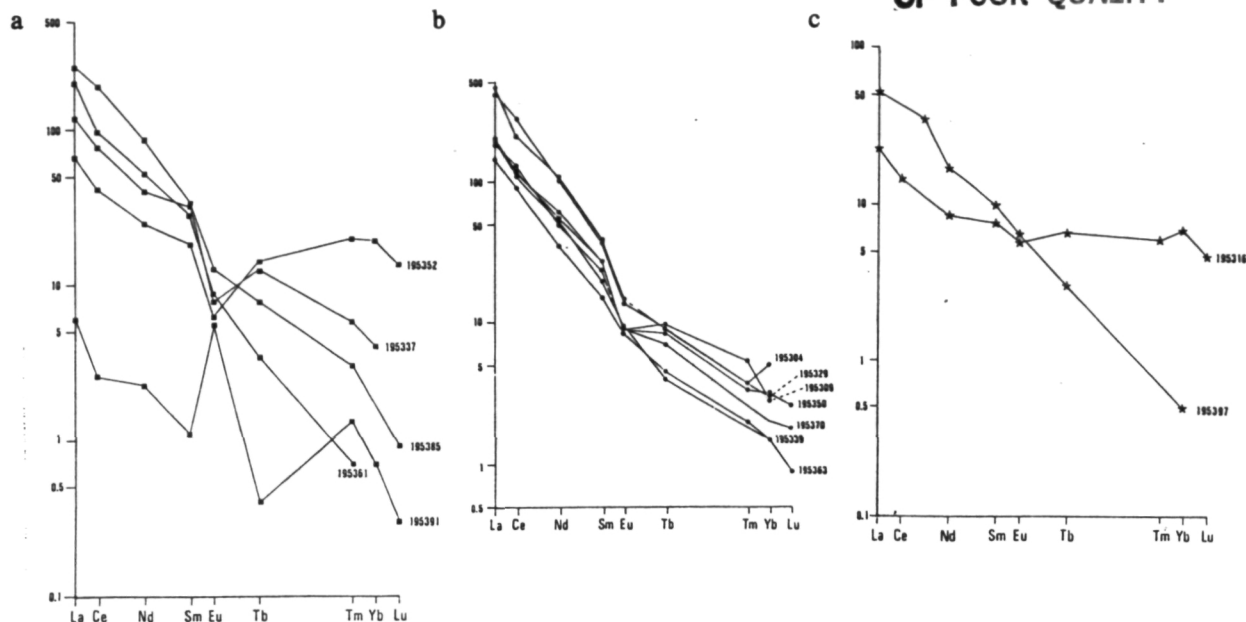


Fig. 14. Chondrite-normalized REE pattern for (a) group 1 granites; (b) group 2 granites; (c) group 3 granites.

sampled. The intrusion of the complex as many small pulses of magma makes the possibility of homogenization of Sr isotopes by convective mixing appear most unlikely.

Undeformed to weakly foliated granites and pegmatite sheets crop out extensively in inner Godthåbsfjord, but are more patchily distributed over a broader area than to the south (Friend and Hall, 1977; Coe and Robertson, 1982; Brewer *et al.* 1983, 1984). The larger outcrops are polyphase, sheeted networks. Rb/Sr and Pb/Pb whole rock ages in the range 2615–2490 Ma confirm that these rocks are similar in age to the “main body” of the Qôrqt granite complex.

Rocks mapped at Qôrqt granite south of the mouth of Buksefjorden (Sharpe, 1975) are affected by the deformation in a late, linear belt and are therefore probably older than the Qôrqt granite complex.

### POST-ARCHEAN EVENTS

Proterozoic dolerite dikes are less common in the Godthåbsfjord region than in most other parts of the West Greenland Archean.

The pattern of late faults in the region is interpreted as the result of predominantly simple shear deformation with the greatest principal compressive stress oriented W to NW (Smith and Dymek, 1983). The Kopperfjord fault zone through central Godthåbsfjord has a dextral

transcurrent displacement of 5 km and a zone of deformation and strong alteration under greenschist facies conditions about 100 m wide. Quartz-rich mylonites were produced by intense ductile deformation. Proterozoic faulting, alteration, and related phenomena in the Isukasia area are discussed by Nutman and Rosing (this volume).

Thermal activity at 1550–1770 Ma is indicated by Rb/Sr dates from micas in Amitsoq gneisses from south of the mouth of Ameralik and from the Isukasia area (Pankhurst *et al.*, 1973; Baadsgaard *et al.*, 1976). A mild thermal event at  $1150 \pm 100$  Ma is indicated by fission track ages from sphene, zircon, and allanite (Gleadow, 1978, and personal communication, 1982).

Later intrusions are restricted to a few thin, E-W trending, deuterically altered basic dikes around the mouth of Ameralik, one of which has given a K/Ar age of 57 Ma (Bridgwater, 1970), and thin lamprophyres in the Færingehavn-Qilângårssuit area.

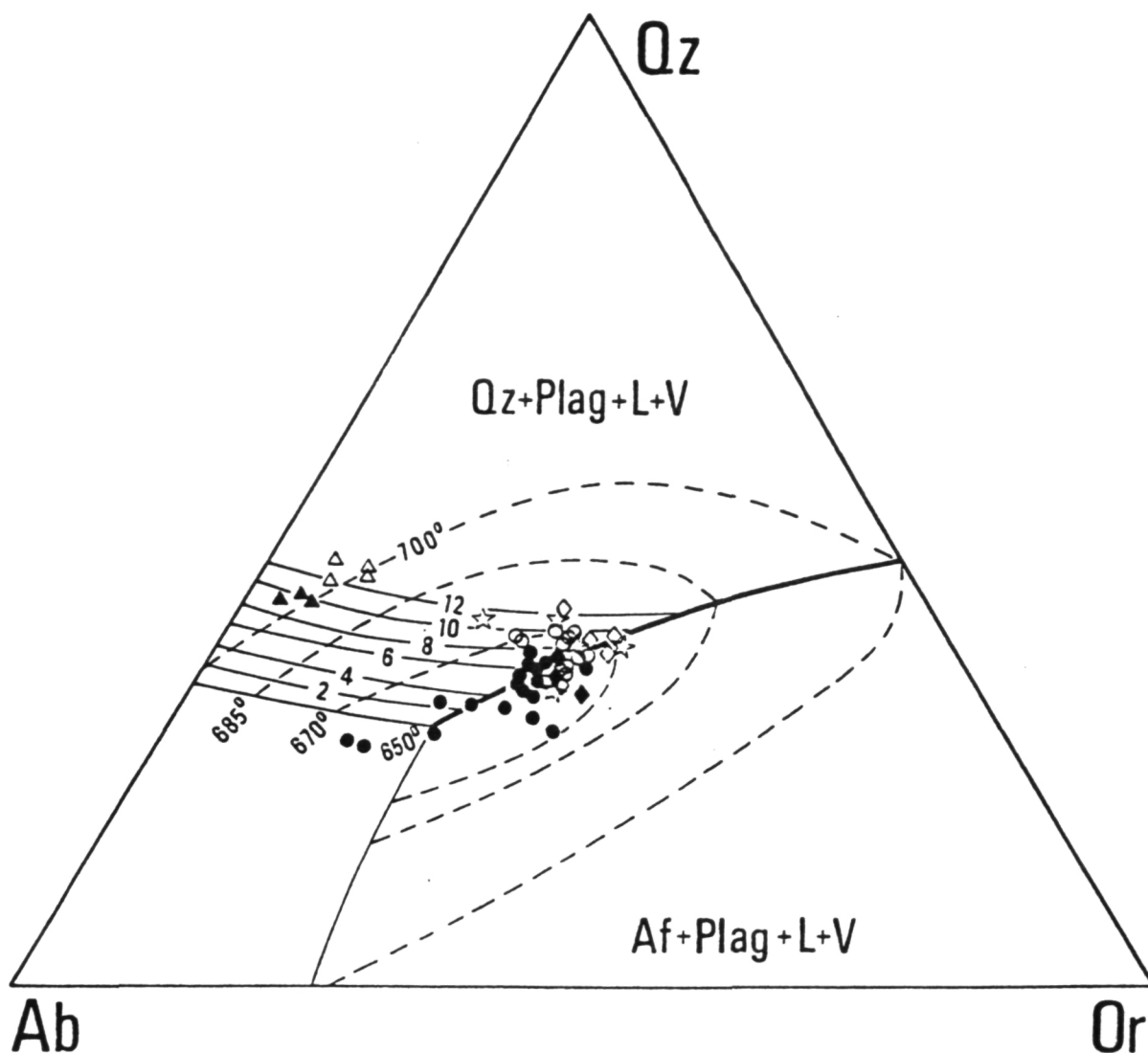


Fig. 15. Analyzed samples from the Qôrqut granite complex plotted with respect to the granite system projected from An onto the base of the tetrahedron. Isotherms on the cotectic surface are projected as dashed lines; also shown are the An contours on the quartz-plagioclase cotectic surface; Symbols: all solid symbols indicate samples that plot above the quartz-plagioclase cotectic surface, open symbols indicate those samples that plot below the surface. Triangles = migmatites; diamonds = group 1 granites; dots = group 2 granites; and stars = group 3 granites.

### Postscript

Some of the hypotheses put forward above must be modified in the light of new discoveries made during our field work in July-August, 1985.

(1) The boundary of the terrain affected by late Archean granulite facies metamorphism in the southern part of the Godthåbsfjord region is sharp and tectonic wherever we observed it from the outer coast south of Færingehavn through Kangerdluarssoruseq, outer Buksefjorden and central Ameralik. It appears to have been a major tectonic

break, probably a thrust. It has been folded and in most places the rocks on either side of it have been strongly affected by post-granulite facies deformation. Between Buksefjorden and Ameralik the tectonic boundary runs close to the eastern of the two anorthositic units that outline the Inugssugssuaq structure, not the western anorthositic unit as indicated in Figure 1. The boundary crosses Ameralik, is folded around the Nipínganeq synform on the north side of Ameralik, and crosses back to the southern side of Ameralik east of Kangimut sangmissoq.



It is now apparent that the zone enriched in K, U, Th, etc. that extends from Færingehavn through Godthåbsfjord and that includes the Qôrqt granite complex does *not* follow a prograde granulite-amphibolite facies boundary at the present level of exposure. It could, however, be related to such a boundary at depth.

The Nûk gneisses with abundant anorthositic enclaves within the Inugssugssuaq structure and at Naujánguit (locality 3.4) are on the northwestern side of the tectonic boundary, within the block that did not reach granulite facies grade in the late Archean. Thus the relationship of these gneisses to the late Archean granulite facies metamorphism cannot be deduced from field relations.

The tectonic boundary runs between the unit of presumed Amîtsoq gneisses at Qasigiánguit-Kangimut sangmissoq and the type Amîtsoq gneisses in outer Ameralik.

(2) A prograde granulite-amphibolite facies transition was observed in one area in inner Bjørnesund, south of Fiskenæsset. Elsewhere in inner Bjørnesund and the next

fjord to the west (Tasiussarssuaq) the prograde boundaries have been obscured by extensive retrogression to amphibolite facies and by some post-granulite facies deformation. The airborne radiometric survey (Secher and Steenfelt, 1981) does not show any very extensive enrichment in K, U and Th in this area.

(3) Several of the textural features described by us as being characteristic of rocks recrystallized during granulite facies metamorphism in the southeastern part of the Godthåbsfjord region were not developed throughout the granulite facies terrain farther south. Spotty pegmatitic patches in the gneisses occur throughout the terrain affected by granulite facies metamorphism. Pervasive blebby texture in gneisses and abundant mafic pegmatites in basic rocks were not observed near the original prograde boundaries, but first appear farther north, around Fiskenæsset. Big-hornblende pegmatites were observed only in the northernmost part of the terrain affected by granulite facies metamorphism.

## EXCURSION GUIDE

## EXCURSION 1

## NUUK TOWN

## Why Nuuk and Nûk?

Over the last 10 years a new orthography for the Greenlandic language has gradually been introduced. Both the new and the old orthography are still used, for example in the newspapers, but the new orthography is now the correct official spelling. The stratigraphic terminology was introduced using the old orthography and this is retained to prevent confusion outside Greenland. Among other things, the new orthography does away with all accents and unsounded consonants. Some examples of spellings in the new and old orthographies are:

Old Orthography	New Orthography
Nûk	Nuuk
Amîtsoq	Amiitsoq
Qârusuk	Qaarusuk
Nagssugtoq (type area for the Nagssugtoqidian fold belt)	Nassuttoq
Itivdleq	Itilleq
Qilângârssuit	Qilangaarsuit
Qôrqt	Qooqut
Ūmánap suvdlua	Uummannap sullua
Kangimut sangmissoq	Kangimut sammisoq

Nuuk (Greenlandic = "the point") is the official name for the administrative capital of Greenland, the Danish name for which is Godthåb. It is the type locality for the mid-Archean Nûk gneisses.

Road cuttings and other blasted sites, the coast southwest of the town, and inland exposures where the lichen has died, all provide excellent exposures of typical polyphase Nûk gneisses with a considerable variety of compositions.

The town area lies within a NNE-SSW-trending belt of late, strong ductile deformation that at a higher level in the crust may have passed into a fault with the western side (Nordlandet) uplifted with respect to the eastern side (the islands and peninsulas in Godthåbsfjord) and with a sinistral (?) strike-slip component of movement. The whole of the peninsula from Nuuk town east past the airport and beyond Store Malene, the high ridge that dominates the view to the east, lies within this deformation belt. To the north, on Bjørneføen, the deformation in the same belt affects late aplitic dikes (Qârusuk dikes, McGregor et al., 1983, see Excursion 4), one of which, outside the deformation belt, has yielded a zircon date of 2660 Ma (Baadsgaard and McGregor, 1981). Movement

in the deformation belt is thought to have overlapped in time with the intrusion of the Qârusuk dikes.

The late deformation has given the rocks in Nuuk town a strong, steeply-dipping planar fabric element that strikes ca. 030°. A regular, linear fabric element that plunges ca. 25° to the SSW is usually conspicuous on foliation surfaces. Both fabric elements are interpreted to be mainly the result of rotation of earlier structures, lithological boundaries, compositional inhomogeneities, etc. into approximate parallelism. Most original discordances between different intrusive Nûk phases have been rotated into concordance. Compare this situation with that seen during excursion 4 in Nûk gneisses on SE Bjørneføen that are part of the same mega-unit, but outside the late deformation belt. There, discordances between intrusive phases are commonly still visible.

The gneisses in Nuuk town enclose and intrude many rafts and enclaves of amphibolite belonging to the Malene supracrustals. These include lithological types with calc-silicate lenses, probably derived from altered pillow lavas, as well as scattered fragments of ultramafic lithologies. Malene amphibolites form extensive rafts cut by sheets of various Nûk gneiss lithologies in the north-west part of the town area and are well exposed on the coast west of the oldest part of the town. Elsewhere in the town area they occur mainly as smaller fragments in the gneisses.

Early, massive dioritic and tonalitic phases make up a belt through the center of the town and contain fewer enclaves of Malene lithologies. The dioritic gneisses form large rafts in the tonalitic gneisses.

A Sm/Nd whole-rock isochron age of ca. 3050 Ma has recently been determined at the University of Alberta on the Nuuk town area samples used for zircon age determinations (H. Baadsgaard, pers. comm.). Rb/Sr and U/Pb systems in most of these gneisses appear to have been affected by later events. An exception is the homogeneous tonalitic gneiss, specimens 152726 and 201415, from Locality 5, Fig. 16, which has yielded a U/Pb zircon concordia intercept date of 2980 Ma with several points on or near the concordia (Baadsgaard and McGregor, 1981). This is the same age as the Taserssuaq tonalite (Garde et al., in press). It suggests the possibility that the belt of more homogeneous tonalitic gneisses that extends through the center of the town area is the extension of the Taserssuaq tonalite, highly attenuated within the late deformation belt.

Eight other specimens from a number of localities within the town area gave considerably more discordant ages in the range 2990-2880 Ma (Baadsgaard and McGregor, 1981). Eleven gneisses that range in composition from dioritic through tonalitic and granodioritic to trondhjemitic, collected from localities across most of the town area, yielded a Rb/Sr whole rock isochron age of 2770

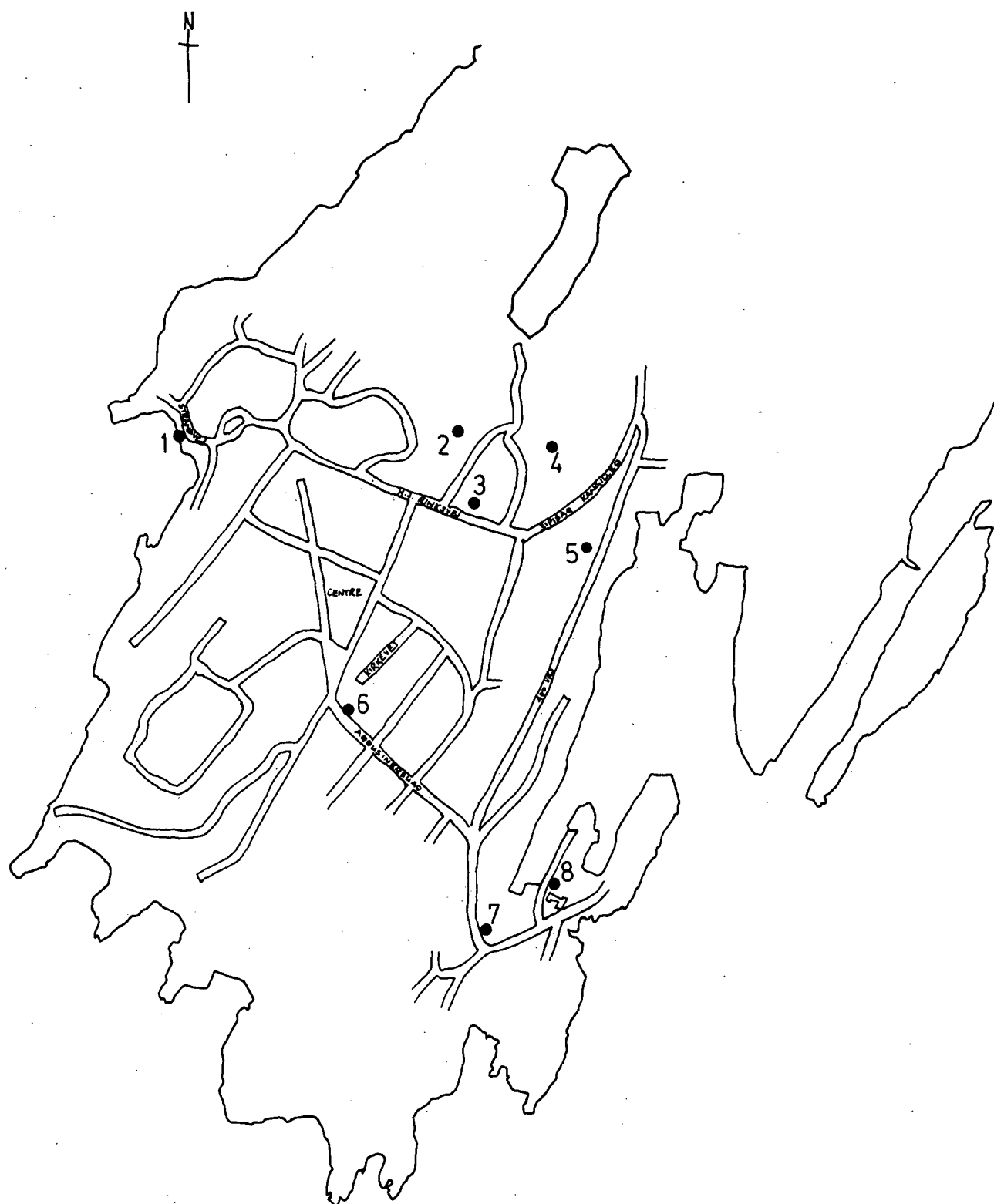


Fig. 16. Localities of some dated and analyzed specimens of Nûk gneisses in Nuuk town.

$\pm 190$  Ma (Taylor et al., 1980). Grant and Hickman (1984) calculated  $T_{UR}^{Sr} = 3388$  Ma for these specimens.

The late deformation belt through Nuuk town separates rocks affected by 3000-2950 Ma granulite facies metamorphism to the west on Nordlandet from rocks that never reached granulite facies to the east. Intense deformation erased almost all evidence of granulite facies metamorphism in rocks in the western margin of the belt where it is exposed on the east coast of Nordlandet. No field evidence has been found to indicate that rocks in Nuuk town were affected by granulite facies metamorphism, but it is a possibility that must be borne in mind. Another possibility is that the isotopic systems were affected by fluids that moved through the deformation belt.

A unit of highly migmatized Amîtsoq gneisses that extends from the islands south of Nuuk to south-west Sadleø (Locality 6.9, Excursion 6) crops out around Nuuk airport. There are few, if any, recognizable Ameralik dikes or early Archean supracrustal rocks in the road cuttings and other blasted sites around the airport. More recognizable Ameralik dikes have been found on the coasts in the western part of the unit.

The following are some of the localities, shown on Fig. 16, where dated and analyzed (Table 3) specimens of Nûk gneisses were collected:

1. Road cutting below and SW of Hans Egede's statue. Sheets of Nûk gneiss separate large rafts of Malene amphibolites. Specimen 131581 is a pegmatite-layered, granodioritic gneiss collected several meters from an amphibolite raft near the western end of the road cutting.

2. Inhomogeneous, "streaky," pale gneisses with migmatized, drawn-out lenses of Malene amphibolites outside the Catholic Church. 131588 is a granodioritic gneiss from the blasted foundation of the chapel.

3. Blasted face behind the Greenland Radio (Kalaallit Nunaata Radioa) building. 131587 is a homogeneous, coarse-textured, granodioritic gneiss. 152725 and 201417 are zircon dated specimens from the same locality.

4. 152724 and 201416 are zircon dated specimens of massive, homogeneous, grey, tonalitic (?) gneiss from a blasted cable line behind the Sports Hall. The zircons are very discordant.

5. Loose blocks of homogeneous tonalitic gneiss left from blasting for the road were collected as specimens 131586 (analysis and Rb/Sr) and 201415 and 152726

(zircon dating). The latter give the most concordant zircon dates in the town area. 152726 was noted to be a little epidotized.

6. Blasted cutting on the north side of road between Magasinet and the bus company's house. There is homogeneous dioritic gneiss (131579) to the west, and homogeneous tonalitic gneiss (131580) which cuts the dioritic gneiss, to the east.

7. Road cutting on the north side of the road just west of the corner. 131582 is homogeneous trondhjemitic gneiss enclosing small, broken-up inclusions of Malene amphibolite.

8. Streaky, granodioritic gneiss (131585) from the road cutting between the Seamen's Home and the marina. Note the strong linear fabric on foliation surfaces.

Table 3. Analyses of Nûk Gneisses From Nuuk Town

	131579	131580	131581	131582	131584	131586	131587	131588
SiO <sub>2</sub>	51.65	65.62	71.76	71.73	67.51	64.48	69.49	70.71
TiO <sub>2</sub>	1.06	0.50	0.20	0.10	0.24	0.56	0.35	0.18
Al <sub>2</sub> O <sub>3</sub>	18.28	16.29	15.11	16.34	17.06	16.40	15.32	15.96
FeO <sup>1</sup>	8.14	3.89	1.06	0.80	1.83	4.17	2.68	1.20
MnO	0.12	0.06	0.01	0.01	0.02	0.05	0.04	0.01
MgO	4.55	1.74	0.46	0.40	1.65	1.85	1.10	0.61
CaO	7.74	3.99	2.10	3.06	2.30	4.47	3.22	2.67
Na <sub>2</sub> O	4.4	4.6	5.3	5.9	5.7	4.6	4.8	5.3
K <sub>2</sub> O	1.59	1.98	2.60	0.99	2.47	1.46	2.18	2.15
P <sub>2</sub> O <sub>5</sub>	0.75	0.26	0.09	0.04	0.05	0.29	0.15	0.08
LOI	0.50	0.58	0.58	0.53	0.49	0.61	0.50	0.48
Total	99.68	99.94	99.39	99.99	99.52	99.41	100.13	99.48
Rb	40	49	47	18	64	46	42	39
Sr	1119	526	735	678	340	690	460	580
Ba	1010	1040	1560	460	520	870	1340	1220
Zn	79	55	21	10	25	53	44	19
Y	19	1	-	-	4	5	5	2
Zr	113	149	138	71	158	150	108	128
Pb	11	14	24	12	22	12	17	15
Nb	6	5	2	3	2	4	2	-
Cr	90	44	22	23	24	50	30	25
Co	28	15	9	12	12	18	11	12
Ni	54	17	-	-	3	21	7	-
U	0.31	0.337	0.51	0.52	0.303	0.37	0.288	0.133

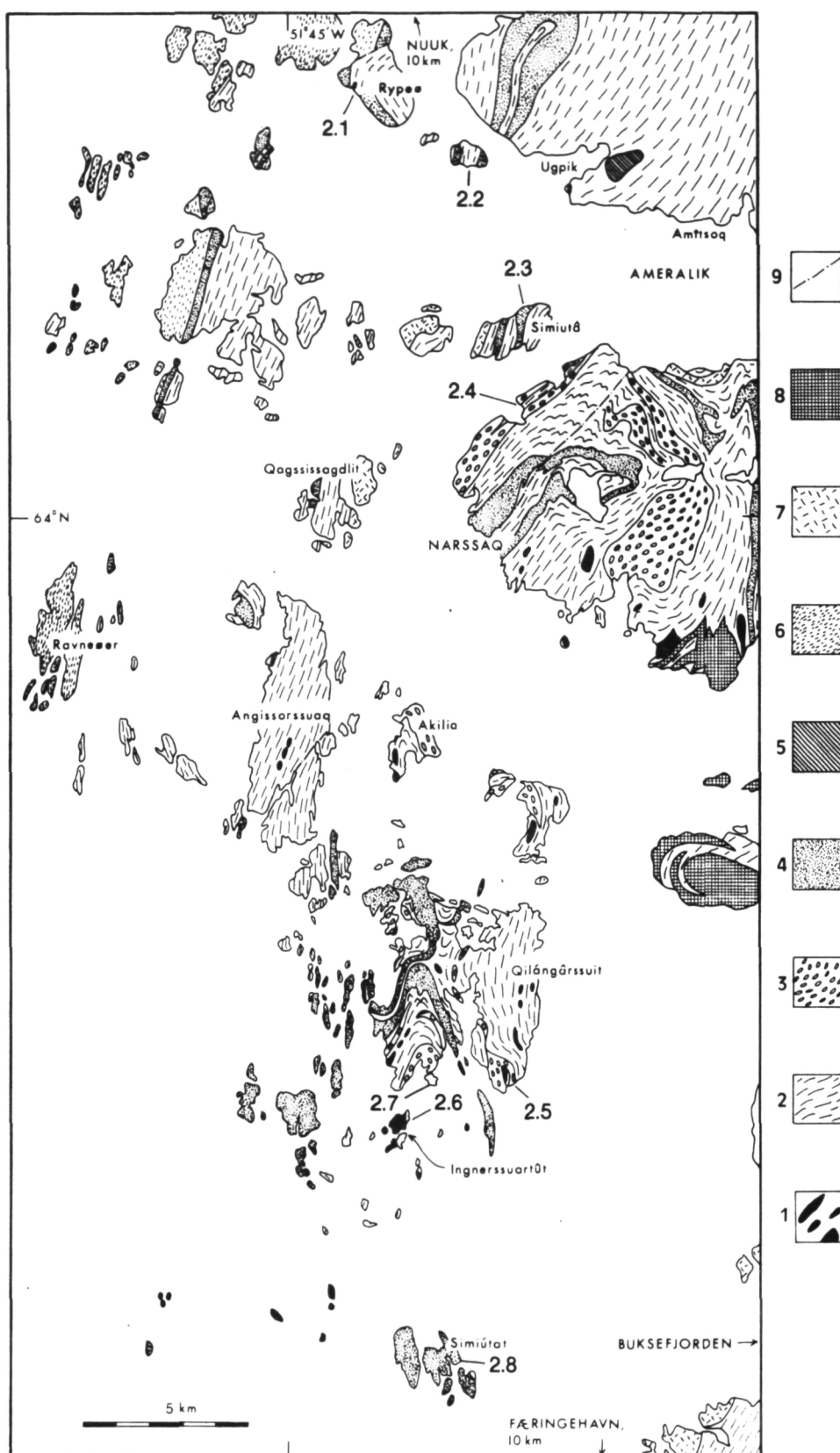
Leeds University XRF analyses, except U, by delayed neutron activation, Risø, Denmark. Major elements in weight percent, minor elements in ppm. Total Fe is reported as FeO<sup>1</sup>. LOI = loss on ignition.

## EXCURSION 2

### NUUK — NORDAFAR — NUUK

Localities for excursion 2 are shown in Fig. 17.

Fig. 17. Geological sketchmap of the outer Ameralik, northwestern Buksefjorden area showing localities for excursion 2. (1) Akilia association; (2) Amîtsoq banded grey gneisses; (3) Amîtsoq iron-rich suite, mostly granodiorite; (4) Malene supracrustal rocks; (5) Ugpik metadolerite; (6) Nûk gneiss; (7) late Archean deformed granitoids; (8) late Archean undeformed granitoids, probably correlating with the ca. 2550 m.y. Qôrqut granite complex; and (9) Proterozoic fault.



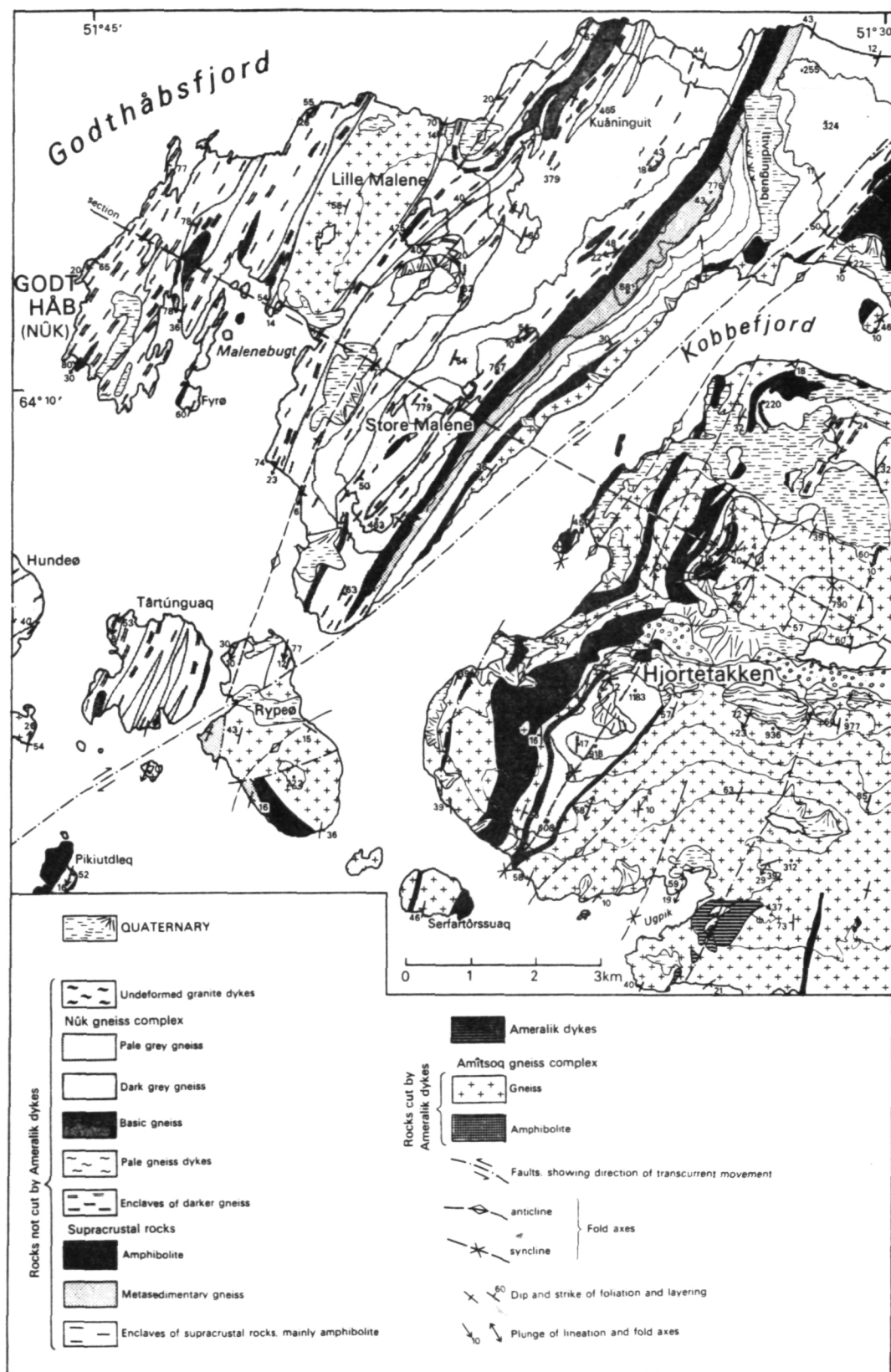


Fig. 18. Detailed map of the area around Godthåb, after McGregor (1973).

As we cross the first stretch of water, between Nuuk and Rypeø, the antiform on Lille Malene can be seen to the north (Figs. 18 and 19). This is one of a row of diapiric domal antiforms that have cores of very homogeneous Nûk granodioritic gneiss. Another of these antiforms will be seen during excursion 4 on southern Bjørneøen (Locality 4.2). Compared with the antiforms to the north, the Lille Malene antiform has been strongly drawn out along a NNE-SSW axis within the late deformation belt.

### Locality 2.1: West Coast of Rypeø

Malene metasedimentary gneisses crop out in two areas, separated by Amîtsoq gneisses, but are probably the same unit. In the southern area they are overlain structurally by Malene amphibolites, which in turn are overlain by Amîtsoq gneisses. Large pods of ultramafic rocks occur along the amphibolite-Amîtsoq gneiss contact. The locality has been described in some detail by Dymek et al. (1983) and copies of their figures are included (Fig. 20).

The Malene metasedimentary gneisses are quartz-rich with abundant plagioclase and biotite and smaller amounts of sillimanite (prominent on foliation surfaces), muscovite, microcline and garnet. Similar lithologies occur only as very thin units elsewhere in the Godthåbsfjord region. REE analyses have been reported by Dymek et al. (1983) and McLennan et al. (1984), and indicate a source for the sediments with REE abundances similar to those in Amîtsoq and Nûk tonalitic gneisses. Sm/Nd characteristics of two samples reported by Hamilton et al. (1983) do not indicate early Archean contributions to the parent sediments.

Only the northern contact between the Amîtsoq gneisses and the Malene metasediments is exposed. We interpret this contact as tectonic and the rocks immediately to the west as including recrystallized cataclasites and intrusive granitoids, the latter now concordant layers of quartzofeldspathic gneiss, as well as gneisses of metasedimentary

origin. Dymek et al. (1983) described a "pod-rock" in the metasedimentary unit near the contact and considered that it could be derived from an intraformational conglomerate or from interlayered sandy to silty sediments. We consider that it may be derived from mica-rich metasediments cut by thin granitoid veins and then highly deformed. Very similar structures occur on SE Bjørneøen where rafts of chlorite-biotite-rich ultramafic rocks were cut by thin Nûk veins and then intensely deformed. Deformation was concentrated in the chlorite-mica-rich lithology and the mica-poor Nûk veins were intensely folded and in extreme cases broken up into pods like those in the "pod-rock" on Rypeø. The Malene units on Rypeø contain other pale grey- to brown-weathering (and in some cases sillimanite-bearing) layers of quartzofeldspathic gneisses of intrusive origin that can easily be taken to be part of the supracrustal sequence. Elsewhere in the region amphibolite units contain sheets of intrusive granitoids, rotated into concordance by strong deformation, that have been described and collected as metasediments.

The Amîtsoq gneiss unit contains a number of thick, tabular bodies of amphibolite interpreted as derived from Ameralik basic dikes. They contain leucocratic symplectic ovoids that are secondary after garnet. The gneisses also contain rafts of other lithologies (Akilia association) that include mafic and ultramafic rocks and a thin layer of quartz-magnetite-actinolite-diopside ironstone.

The Amîtsoq gneiss unit is cut by a dolerite dike that is presumed to be Proterozoic and, near the contact with the southern area of metasediments, by a thin, vesicular, red-weathering dike that is typical of a suite of E-W dikes that occurs around the mouth of Ameralik. A dike belonging to this suite on the north coast of Ameralik between Ugpiq and Amîtsoq has yielded a K/Ar date of  $75.2 \pm 1.1$  Ma (Bridgwater, 1970).

Looking up Kobbefjord, between localities 2.1 and 2.2, one can see abundant large pegmatites in the Malene supracrustal unit on Store Malene. They are presumed

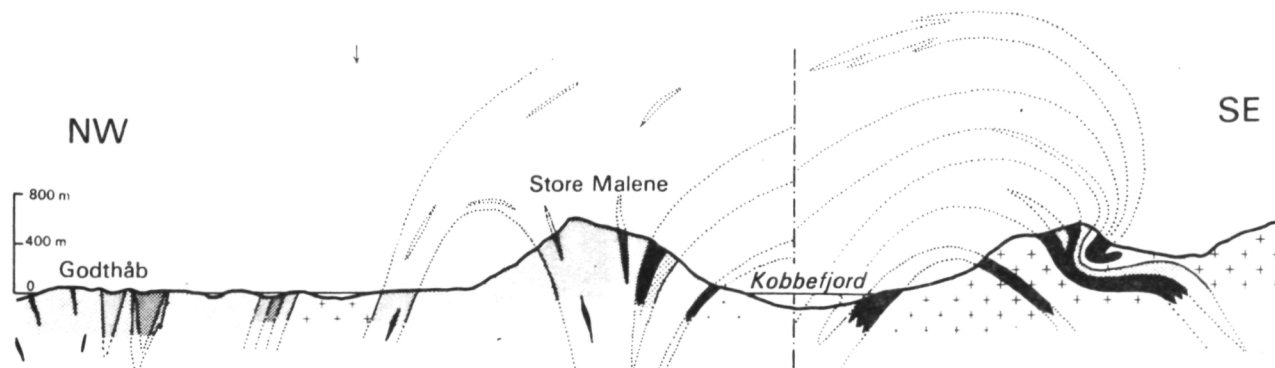


Fig. 19. Geologic section corresponding to dashed line in Fig. 18, after McGregor (1973).



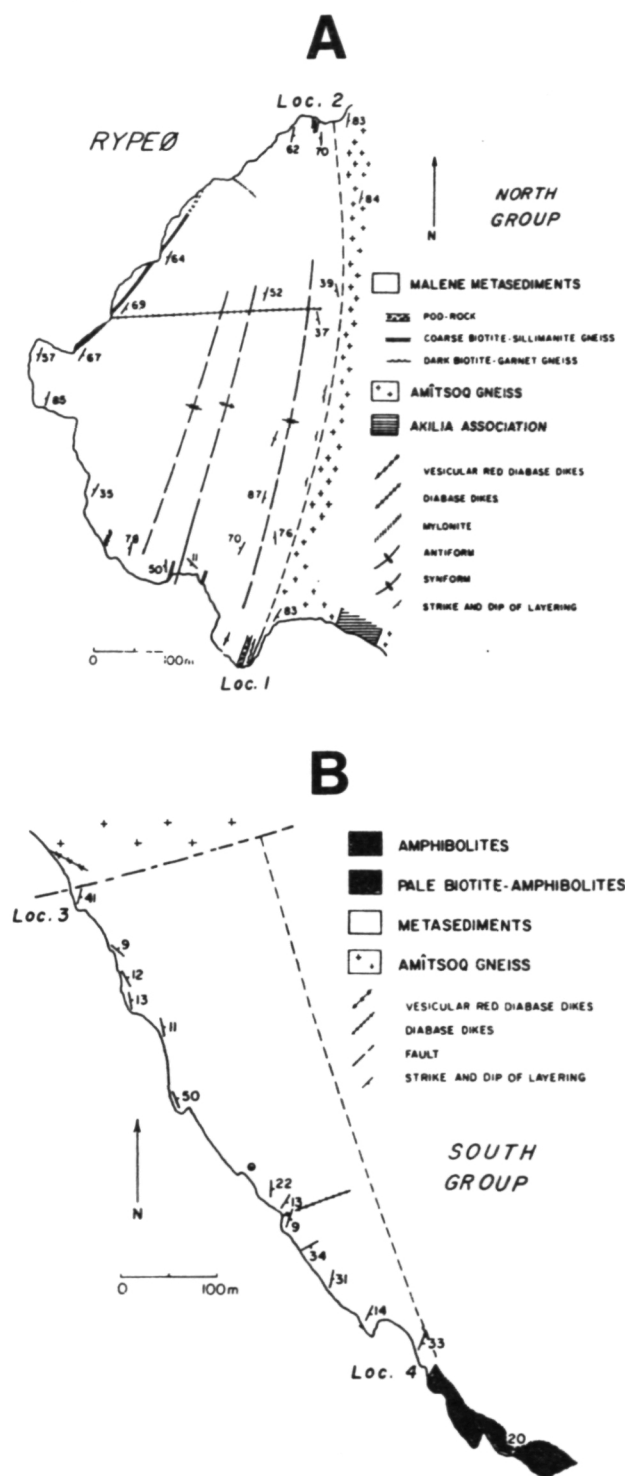


Fig. 20. A: Geology of the northern group of Malene metasedimentary rocks on Rypeø. Akilia association refers to supracrustal (?) enclaves in Amitsoq gneiss as defined in McGregor and Mason (1973). B: Southern group of Malene supracrustal rocks on Rypeø. Both A and B from Dymek et al. (1983).

to be the same generation as little- or undeformed pegmatites in the same Malene unit on Sadleø to the north (see the Qôrqut 1:100,000 map sheet), which have the form of giant tension gashes. The pegmatites on Store Malene, within the late deformation belt, are folded. The original orientation of the pegmatites, as seen on Sadleø, and the folds on Store Malene are taken to indicate the sense of movement in the deformation belt (Fig. 21).

#### Locality 2.2: Serfartôrssuaq

Intercalation of Amitsoq gneisses, Malene supracrustal amphibolites and Nûk gneisses can be seen on the mountain face to the north-east (Figs. 19 and 20). Two different units of Malene supracrustal rocks are visible; a thicker unit to the west (unit C) that is the core of a re-folded, isoclinal, recumbent fold, shown in Fig. 19, and a thinner unit (unit D) that outlines a synform with a core of massive, pale Nûk gneiss. Unit C contains much folded pale pegmatite and gneiss. The two Malene units are separated by a thin unit of well-layered Amitsoq gneisses and by more massive Nûk gneisses intruded along the eastern contact of unit C.

Part of unit C and the thick Amitsoq gneiss unit to the west are well exposed on the south coast of Serfartôrssuaq. The Amitsoq gneisses are well-layered, variable, mainly pale gneisses. They enclose thin, continuous, concordant Ameralik dike amphibolites. One of these that is poorly exposed, but that occurs as detached blocks on the coast, contains the characteristic calcic plagioclase clots. The Akilia association is represented by a few thin layers of laminated amphibolite and a broken-up layer of striped, green-and-black clinopyroxene-hornblende rock. There are many concordant, deformed pegmatites, probably several generations.

The contact between the Amitsoq gneisses and the Malene supracrustal unit is concordant. The western part of the Malene unit is made up of finely laminated ("striped") black and dark green-brown amphibolites that are most likely derived from very highly deformed, altered pillow lavas. To the east, in the core of the isoclinal fold, amphibolites are interlayered with garnet-, anthophyllite-, cordierite-, and staurolite-bearing lithologies. The supracrustal unit contains sheets of strongly deformed pegmatite and grey gneiss Nûk type.

#### Locality 2.3: Simiutâ

On Simiutâ, Malene supracrustal units dominated by amphibolite are separated by gneisses with concordant tabular amphibolites. The gneisses are probably dominantly early Archean, but there are also late Archean granite and pegmatite sheets. The supracrustal rocks may all be the same unit repeated by folding. Symmetrical arrangement of lithologies suggests that the eastern



supracrustal unit is the core of an isoclinal fold. Thin sequences of quartzose rocks, interpreted as metasediments, occur along both contacts between the amphibolites and the enclosing gneisses.

On the north coast, the most complete section is: Amîtsoq-type gneisses with concordant Ameralik dike-type amphibolites; layered quartzite; massive quartzite

(metachert?) with mica schist; layered amphibolite with ultramafic pods. Thicknesses of the Malene lithologies vary considerably along strike, probably because of heterogeneous strain, and tectonic slides have been identified locally. The layered quartzites (243057c, Table 4) are aluminous and contain zircons. Layering is continuous laterally with respect to its thickness. The

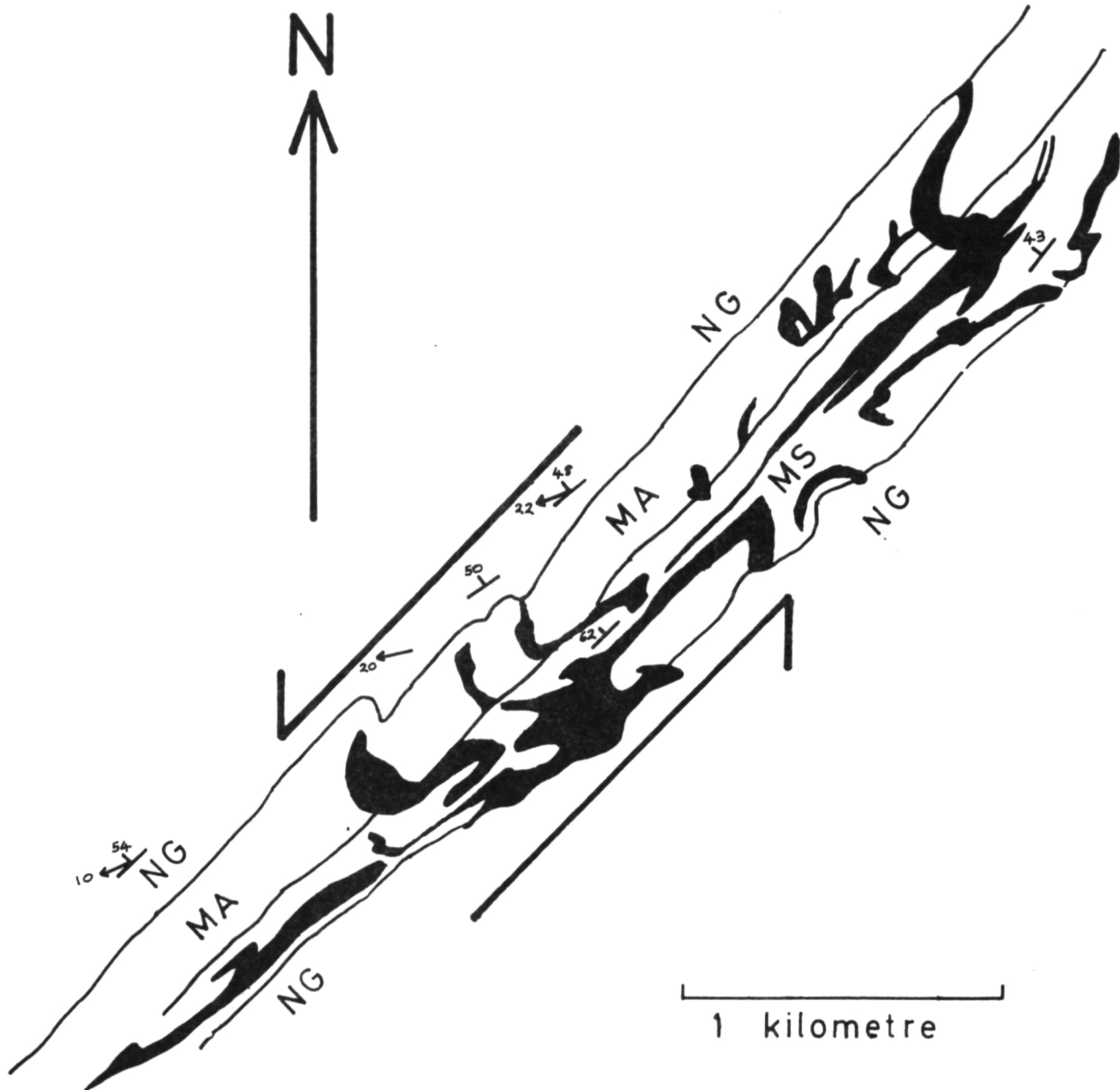


Fig. 21. Deformed (?) Qârusuk pegmatites in the Malene supracrustal unit on Store Malene. The pegmatites are assumed to have been formed as giant tension gashes with NW-SE orientation like those on Sadleø. This orientation has been retained in the more competent Malene amphibolites (MA), while they have been rotated into concordance with the layering of the Malene metasediments (MS). The pattern suggests simple shear deformation with a large vertical component in addition.

massive quartzites are coarse-grained and have a vague layering defined by flecks of amphibole. The associated mica schists are weakly layered and consist mostly of biotite and chlorite with some quartz and feldspar. Locally they have knots of greenish-weathering (Cr-bearing?) white mica. They are rich in Fe, Mg, Ni and Cr and may be sediments derived by weathering of penecontemporaneous basic volcanics. The amphibolites include variable banded types, some with pods of calc-silicate minerals, as well as sheets of very homogeneous amphibolite. The unit contains large pods of peridotite and hydrated equivalents, which may be olivine-pyroxene cumulate facies of layered basic flows or sills.

Nutman and Bridgwater (1983) have interpreted the contact between the quartzites and the Amîtsoq gneisses as a deformed unconformity and the quartzites themselves as fairly mature sediments deposited on an Amîtsoq basement. V.R.M. considers it possible that the contact is tectonic and has been "healed" by intense deformation and metamorphic recrystallization. Quartzites are rare in the Malene supracrustal rocks, but are known to occur locally within amphibolite units, and therefore not only along Malene-Amîtsoq contacts.

#### Locality 2.4: Kanajorssuit

Augen gneiss (deformed big-feldspar granodiorite, analysis 162475, Table 4) of the Amîtsoq iron-rich suite is unusually well preserved here in a small area of low deformation. The effects of progressively stronger deformation on the gneiss and on Ameralik dikes that cut it can be observed along the coastal outcrops to the south.

Where least deformed, the augen gneiss has more or less randomly oriented microcline microperthite megacrysts in a matrix of quartz, plagioclase, microcline and mafic minerals. The microcline augen comprise relic, single-grain cores surrounded by recrystallized, polygranular aggregates. In rocks where the augen have deformation ratios of more than about 10:1 they are completely recrystallized to granular aggregates. Gancarz and Wasserburg (1977) reported Pb isotopic abundances and other data from feldspar megacrysts from this locality.

Biotite and hornblende are commonly concentrated in clots that also contain apatite, zircon, sphene and magnetite-ilmenite. Where least deformed the augen gneisses range from completely isotropic through rocks with faint igneous (?) layering defined by slight concentrations of mafic minerals to very heterogeneous rocks containing irregular concentrations of mafic minerals. They contain quartzofeldspathic and amphibolitic inclusions, several of which are mantled by concentrations of the mafic clot material. Microcline

megacrysts have grown within and across the contacts of some inclusions.

Along the coast to the south the augen gneiss and Ameralik dikes are progressively more deformed. A marked foliation is developed in the gneiss and the microcline augen become smeared out. Ameralik dikes are folded and progressively broken up. To the south, strongly deformed augen gneiss is in contact with Amîtsoq layered grey gneisses that contain trains of highly broken-up Ameralik dike amphibolites. The fabrics in the gneisses on either side of the contact are parallel. This locality illustrates clearly how difficult it can be to recognize and distinguish different lithologies in the gneiss complexes where, as is normally the case, they are strongly deformed.

#### Locality 2.5: South-East Corner of Qilángárssuit

Augen and ferrodioritic gneisses of the Amîtsoq iron-rich suite are separated by Amîtsoq layered grey gneisses. Augen gneisses were first described here in the early 1800s by Giesecke, the first geologist to work in West Greenland! Berthelsen (1955) described in considerable detail the ferrodiorite and the Ameralik dike that cuts it (Fig. 22).

The ferrodiorite (analysis 155734, Table 4) occurs as a folded sheet ca. 50 m. thick and is rather homogeneous. An area of brown-weathering rock several meters in diameter near the center of the body preserves the assemblage  $\text{opx-cpx-gnt-plag} (\text{An}_{28})\text{-hbd-qtz}$ , which is interpreted to be a relic from the early Archean granulite facies metamorphism. The ferrodiorite is cut by big-hornblende pegmatites like those found in dioritic and tonalitic lithologies affected by late Archean granulite facies metamorphism in the south-east part of the Godthåbsfjord region. Layered Amîtsoq grey gneisses to the west have strongly deformed blebby texture, suggesting that they too are retrogressed from granulite facies, but there is no evidence of previous granulite facies metamorphism in Ameralik dikes in this area, with the possible exception of the dike that cuts the eastern part of the ferrodiorite. Towards its margin, the ferrodiorite has moderately strong foliation and has been retrogressed to amphibolite facies. Contacts with the enclosing layered grey gneisses are sharp and conformable, the result of deformation.

The metamorphosed basic dike that cuts the eastern part of the ferrodiorite is clearly discordant to the folded foliation of the diorite. It contains relic megacrysts of plagioclase that have sericitized cores surrounded by recrystallized aggregates of clear plagioclase (ca.  $\text{An}_{70}$ ). The dike contains hornblende-bearing segregation pegmatites that have some similarity to the mafic pegmatites found in basic rocks retrogressed from granulite facies (Figs. 5 and 6). It contains other

segregation pegmatites composed mainly or entirely of plagioclase  $\pm$  quartz and bordered by mafic extraction zones. This type of segregation pegmatite (c.f. Fig. 7), which is also seen in Ameralik dikes at locality 2.7, developed under amphibolite facies conditions.

A thicker, more typical Ameralik dike is separated from the western contact of the ferrodiorite by a thin slice of grey gneiss. It was misidentified by Berthelsen as an apophysis of the diorite. To the west there are typical Amîtsoq layered grey gneisses that inland border a raft of layered ultramafic rocks (Akilia association). Around the point to the west they are in contact with rather massive Amîtsoq augen gneiss from which Ameralik dikes are absent. It is unusual, outside the Isukasia area, to find a section of Amîtsoq gneisses as thick as this with no Ameralik dikes.

#### Locality 2.6: Ingerssuartût

A wide range of supracrustal and intrusive basic and ultrabasic rocks belonging to the Akilia association are exposed on this group of islands (Fig. 23). An unusually thick, layered Ameralik dike crops out on the eastern and southern islands, but elsewhere there are only a few thin Ameralik dikes.

An early layered sequence includes banded iron formation (with combinations of quartz, magnetite, grunerite, Fe-rich orthopyroxene, clinopyroxene, garnet,

actinolite and sulphides) and layered amphibolites with subordinate ultramafic rocks, quartz-biotite-sulphide gneisses, felsic gneisses and clinopyroxenites. The layered amphibolites and metasediments are interlayered on scales of less than 1 meter to more than 50 meters. In places there is evidence of secondary silica penetration of the layered rocks. The chemistry of the best preserved amphibolites suggests that they are predominantly of Archean picritic to Fe-tholeiitic affinity.

The layered sequence is cut by thick, locally discordant bodies of leuco-amphibolite that are weakly laminated in places. They have geochemical affinities with some strongly fractionated komatiitic liquid compositions.

Relic cores with early Archean granulite facies mineral assemblages are preserved locally, for example in layered basic rocks on the low island south-east of the largest island and connected to it at low tide, and in banded iron formation on the south-west coast of the largest island. The thick Ameralik dike on the eastern and southern islands has garnet-bearing, higher grade cores, but has not been found to contain orthopyroxene. It thus appears to post-date the granulite facies metamorphism.

There are thin, post-Ameralik dike sheets of grey gneiss on the northern part of the largest island and many little- or undeformed sheets of biotite-bearing pegmatite and microgranite that here, as elsewhere in the Qilángarsuit area, commonly trend E-W.

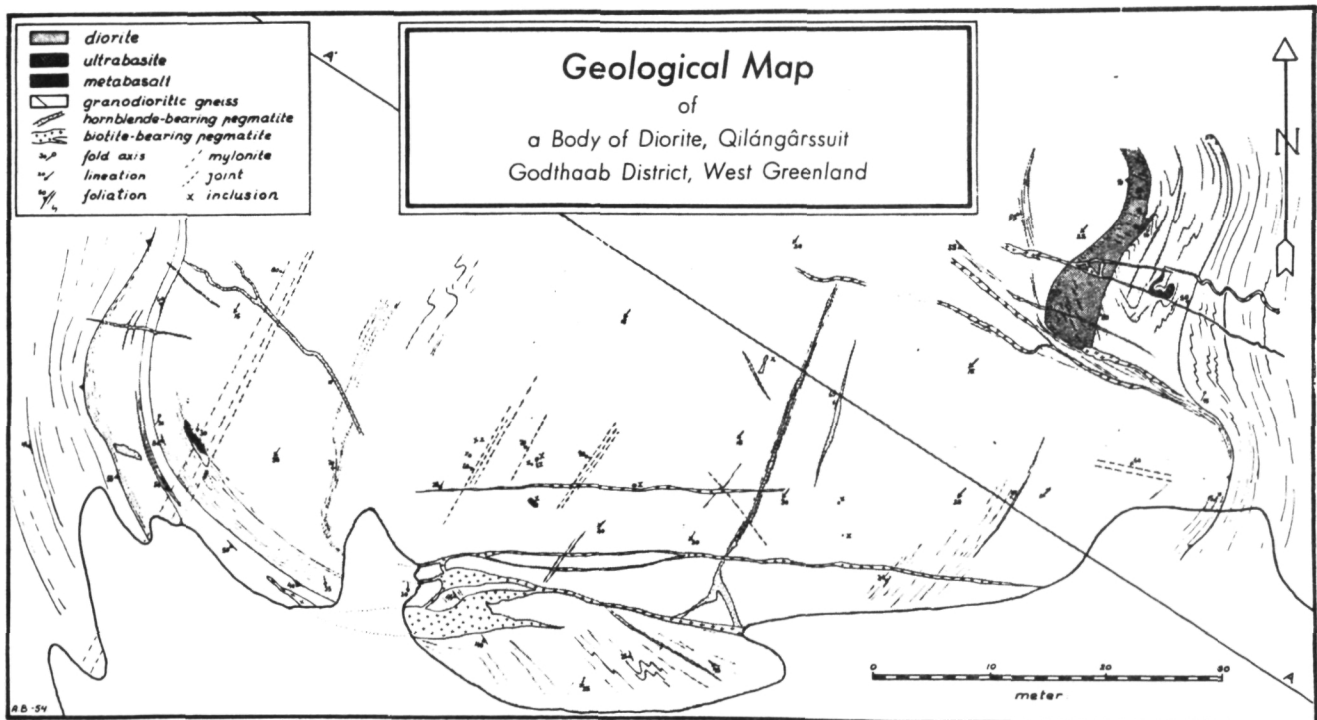


Fig. 22. From Berthelsen (1955).

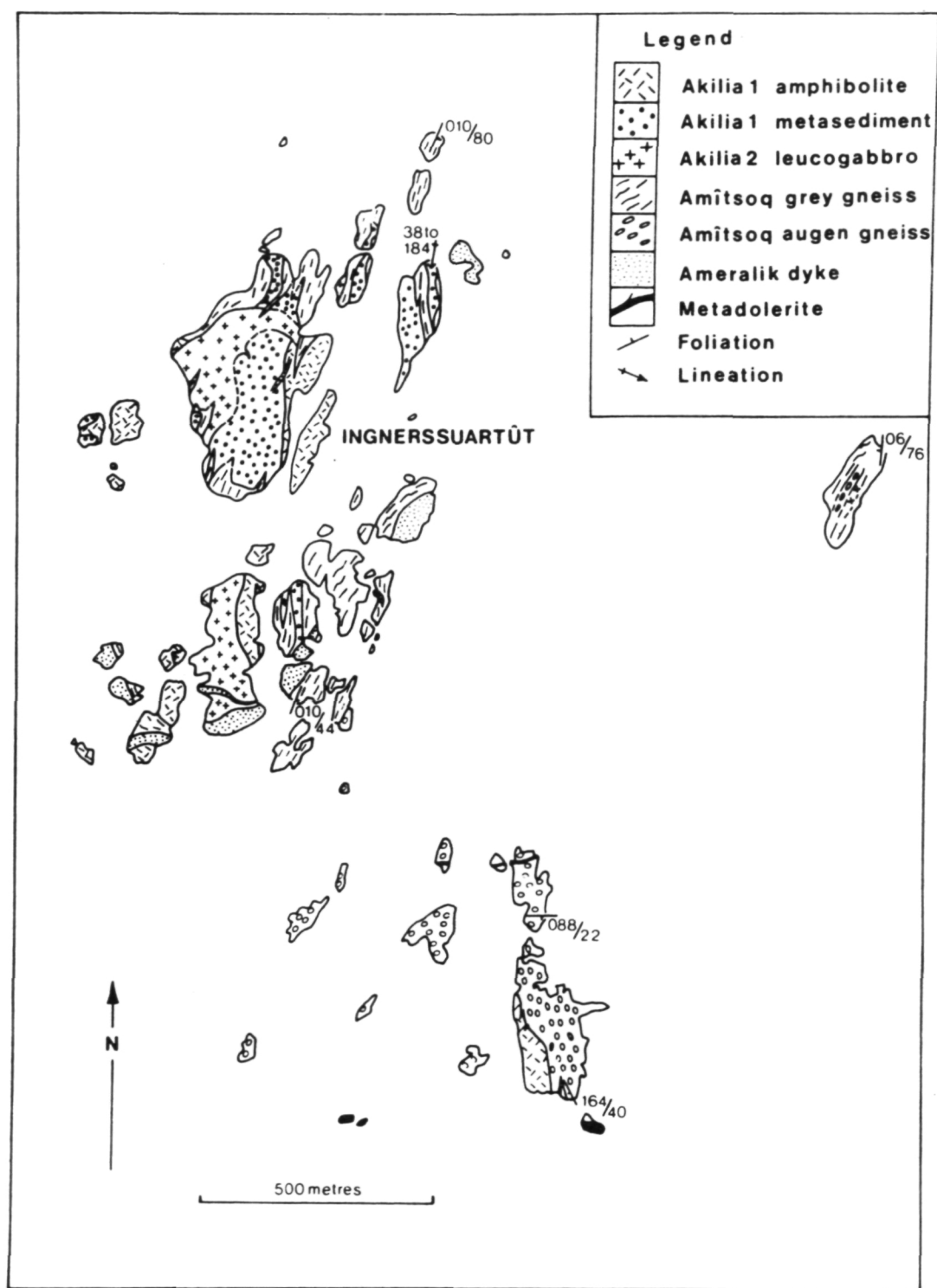


Fig. 23. Geological map of Ingnerssuartût and nearby islands, from Griffin et al. (1980).

### Locality 2.7: Island Between Ingnerssuartût and Qilángárssuit

At this locality Amîtsoq gneisses and Akilia basic rocks, which are in an area of unusually low late Archean deformation in the core of a synform, preserve textural evidence of early Archean granulite facies metamorphism.

Because of the low deformation, most Ameralik dikes at this locality are still clearly discordant. There are several types that range from ultramafic to leucoamphibolite in composition. Some dikes contain very scattered, small plagioclase megacrysts. On the south side of the island a homogeneous mesocratic Ameralik dike is cut by a rusty-weathering leucocratic Ameralik dike with many pegmatitic segregations. Both dikes are strongly discordant to the layering in the gneisses. At the western end of the island there is a strongly folded, broken-up ultramafic dike and nearby a thicker dike with a pattern of segregation pegmatites. The segregation pegmatites in Ameralik dikes at this locality are all of the type with leucocratic cores that formed under amphibolite facies conditions (see locality 2.5). Note the relatively wide spacing of Ameralik dikes at this locality compared with more typical Amîtsoq gneiss exposures seen elsewhere, where strong late Archean deformation has telescoped together and thinned the originally more widely spaced, thicker Ameralik dikes. The Ameralik dikes here are totally recrystallized to lineated hornblende amphibolites, showing that all the rocks at this locality recrystallized under middle-upper amphibolite facies conditions in the late Archean.

Nonetheless, because of the low degree of late Archean flattening deformation, early Archean textural features that indicate recrystallization under granulite facies conditions are preserved locally. The polyphase, pegmatite-streaked, grey gneisses have patches with clear relic blebby texture, spotty pegmatitic areas and big-hornblende pegmatites, features comparable to those seen in areas retrogressed from late Archean granulite facies metamorphism (localities 2.10 and 3.3). These features are truncated at the discordant margins of Ameralik dikes, and it can be seen that the relic granulite facies textures were deformed before the Ameralik dikes were intruded. There are abundant mafic pegmatites and ultramafic segregations, both indicators of previous granulite facies recrystallization, in rafts of layered Akilia amphibolites. Comparable features are absent from the Ameralik dike amphibolites. This is clear evidence that the Ameralik dikes here post-date the granulite facies metamorphism, which must therefore have occurred in the early Archean. Near the western end of the island there is a large raft of Akilia metagabbro that is cut by a discordant Ameralik dike.

There are a few zones, e.g., near the western end of the island, where the degree of late Archean flattening deformation is greater. Note how the Amîtsoq gneisses in these zones take on a rather simple, regularly layered appearance. It is clear that both early- and late-Archean deformation must have erased the complex early history of the Amîtsoq gneisses in most places. As a general rule, the layered grey gneisses that form much of the Amîtsoq gneisses cannot be used to provide *detailed* information on the nature of early Archean crust formation.

### Locality 2.8: Simiútat

Malene supracrustal rocks, especially metasedimentary gneisses, are more varied and better exposed on this group of islands than anywhere else in the region. The geology of the islands is shown on Fig. 24, which has been drawn for this excursion guide by Dr. Brian Chadwick, University of Exeter.

We visit a locality where Malene quartz-cordierite-anthophyllite-sillimanite gneisses are well exposed. The very unusual composition of this lithology is shown by analysis 131490, Table 4, of a specimen from the same unit on Sagdlerssua, an island just to the northwest. More analytical data can be found in Beech and Chadwick (1980). Dymek (1983) has shown that the rutile in this lithology is unusually rich in Nb. In places it can be seen with the naked eye. Cordierite, anthophyllite and sillimanite can be found as very large grains. It is clear from the geological relations of the unit here that the rock cannot be the product of local metasomatic action, but must have been laid down as a thick, extensive unit in the supracrustal sequence. Note also the complete lack of any amphibolites of Ameralik dike type. The unit contains lenses rich in garnet that locally enclose relics of staurolite.

### Localities 2.9-2.12: Kangerdluarssoruseq (Færingehavn fjord)

At these localities (Fig. 25) we see early Archean rocks on both sides of the late Archean prograde granulite-amphibolite facies boundary. The granulite facies mineral assemblages have been almost totally retrogressed to amphibolite facies, but the rocks retain textural features that were developed under granulite facies conditions. They have been affected by strong post-granulite facies deformation that included major folding and the development of a late "straight belt" of intense ductile deformation similar to the deformation belt through Nuuk town. The rocks on the amphibolite facies (western) side of the metamorphic facies boundary were intruded by late granitic ("white gneiss") and pegmatitic sheets that may well have been generated by anatexis of rocks

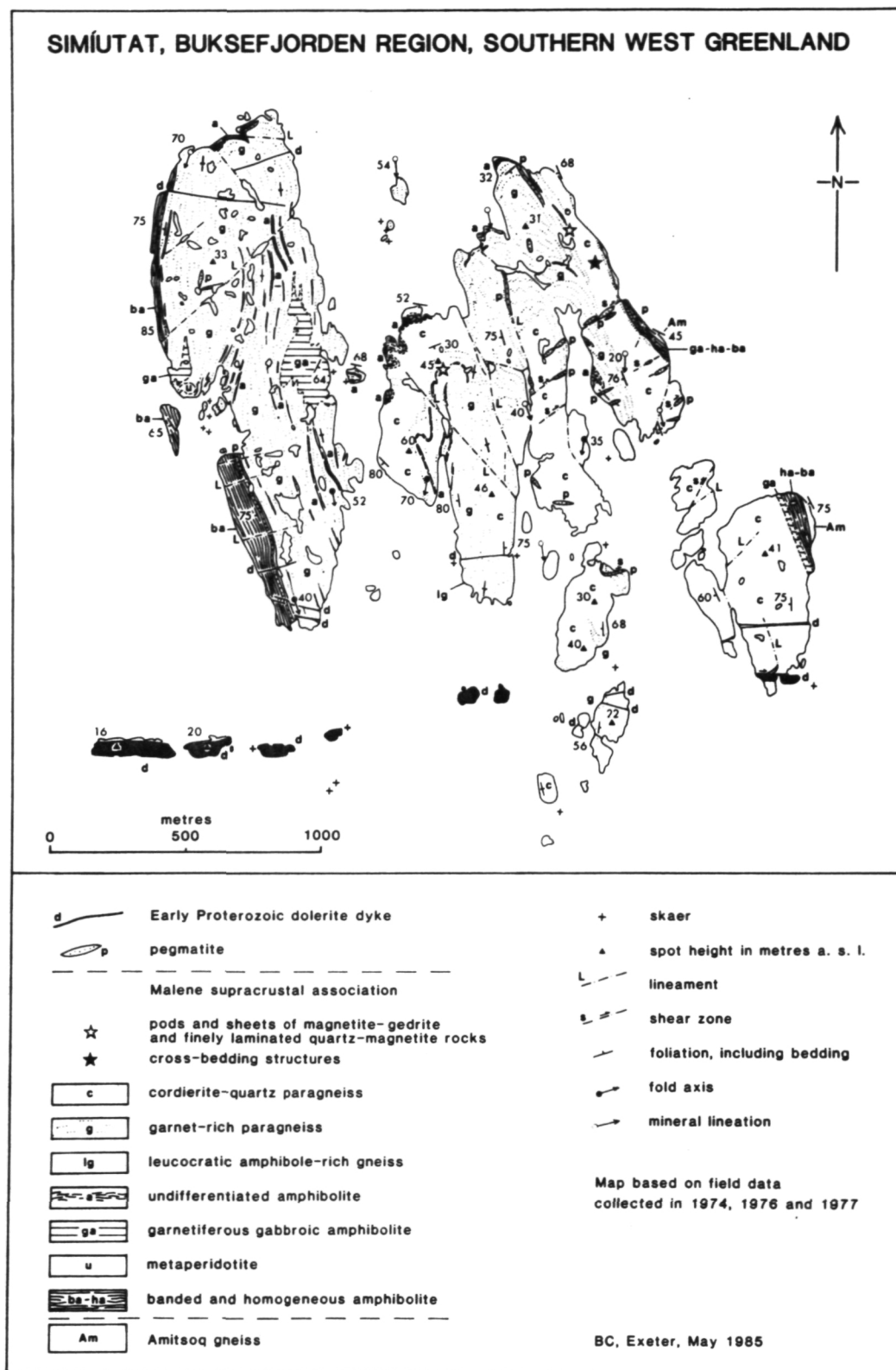


Fig. 24. Geological map of Simiútat drawn by Dr. Brian Chadwick, University of Exeter.

enriched in elements expelled from deeper levels that suffered granulite facies metamorphism. The late granitic rocks were affected by the "straight belt" deformation.

**Locality 2.9:**

Relic cores in a migmatized basic unit of uncertain but probable Akilia affinity contain abundant orthopyroxene, together with hornblende, especially in mafic pegmatites and ultramafic segregations. They can be

followed through rocks in which orthopyroxene is progressively replaced, first by fibrous brown amphibole and then by black hornblende, into adjacent amphibolites that are totally retrogressed to amphibolite facies. The gneisses that intrude the basic rocks preserve clear blebby texture locally in low deformation areas, but have mainly suffered very intense deformation that destroyed textural evidence of granulite facies metamorphism.

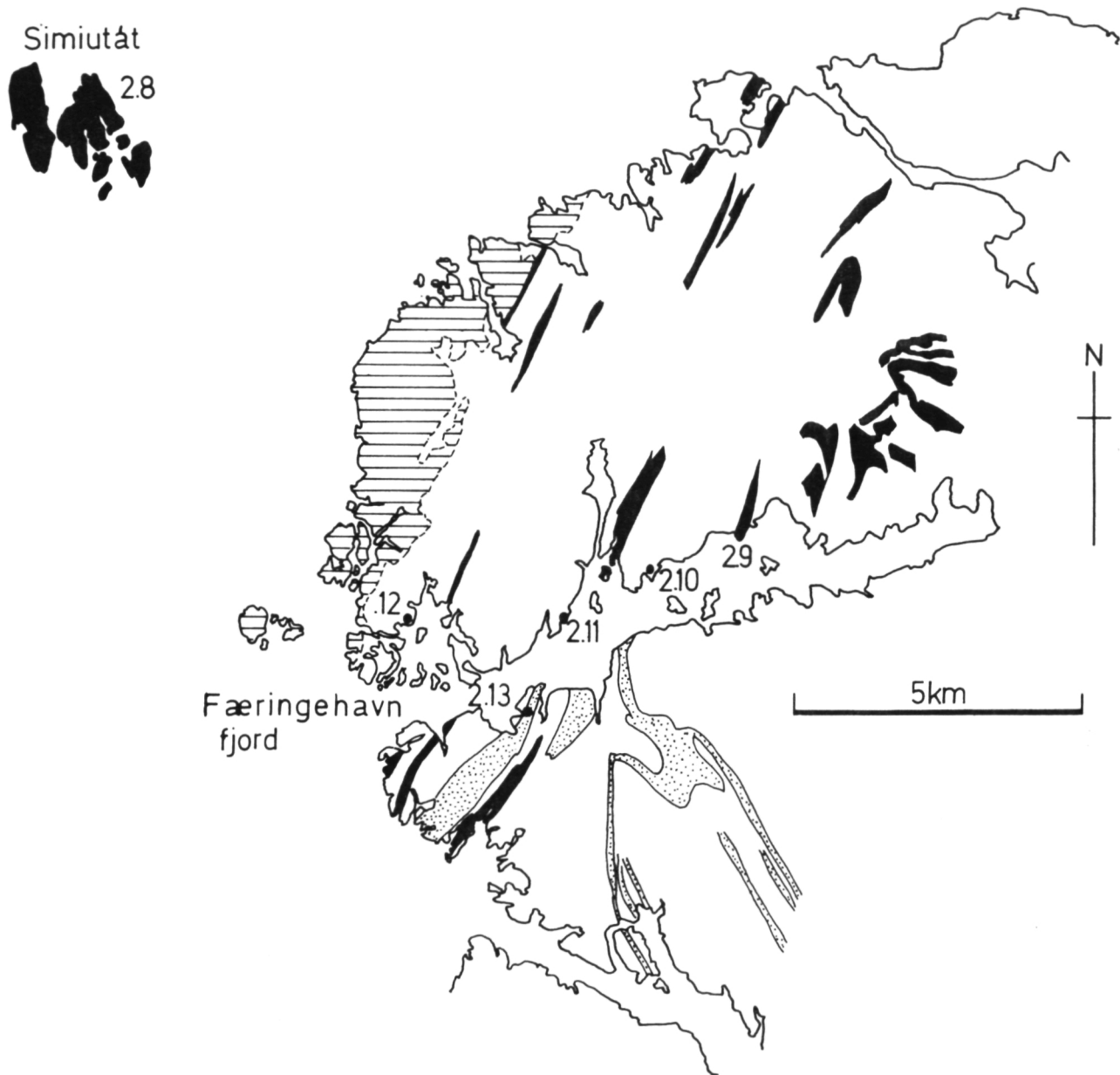


Fig. 25. Excursion localities in Kangerdluarssoruseq. Geology from 1:100,000 Buksefjorden map sheet. Black = supracrustal and basic rocks; dotted = anorthositic rocks; ruled = late granitic gneisses and pegmatites.



**Locality 2.10:**

Amîtsoq gneisses with relatively unbroken Ameralik dike amphibolites contain abundant textural evidence of late Archean granulite facies metamorphism:

1. pervasive blebby texture in the gneisses,
2. most of the layered structure in the gneisses has been lost and the gneisses have become nebulitic,
3. mafic pegmatites and ultramafic segregations in Ameralik dikes,
4. relic orthopyroxene or fibrous, brown amphibole secondary after orthopyroxene.

From this locality we walk along the coast towards the west and observe how textural indications of granulite facies metamorphism in the Amîtsoq gneisses and the common, thin sheets of Ameralik dike-type amphibolite have been modified by strong "straight belt" deformation.

**Locality 2.11: Nordafar**

The rocks at Nordafar appear to be just outside the original prograde granulite facies boundary, but relations are complicated by late deformation.

On the coast just west of the Seamen's Home, Amîtsoq gneisses with Akilia association lithologies that include striped green-and-black clinopyroxene-hornblende rock are cut by clearly discordant Ameralik dike amphibolites, several of which contain the characteristic plagioclase clots. The rocks are cut by late white gneiss-pegmatite sheets. There is scattered blebby texture in the gneisses, especially in more mafic areas, but no evidence of previous granulite facies metamorphism in the Ameralik dikes (no mafic pegmatites or ultramafic segregations). This situation (textural evidence of previous granulite facies metamorphism in Amîtsoq gneisses, but none in enclosed Ameralik dikes) holds throughout the outer part of Kangerdluarssoruseq and the islands to the south-west, and leads us to conclude that the blebby texture in the gneisses dates from the early Archean and not the late Archean granulite facies metamorphism.

Eight Amîtsoq gneisses from this locality yield a poorly correlated Rb/Sr whole rock isochron with an age of  $3001^{+193}_{-153}$  Ma. Nd isotopic data for 3 of the specimens lie within the scatter for the type Amîtsoq gneisses. They yield model ages of between 3400 and 3200 Ma (Collerson et al., this volume).

Eastward the sequence seen on the coast around the bay and near the wharf is:

1. Amîtsoq gneisses as described above.
2. A thin mylonite and pegmatites near the contact to (3).
3. A thin unit of pale, well-layered Malene amphibolite, strongly affected by late deformation.
4. Garnet-bearing Malene metasedimentary gneisses, including quartz-cordierite gneisses.

5. A thin unit of Amîtsoq gneisses with thin, unbroken Ameralik dikes.

6. Rather homogeneous gneiss of Nûk-type.

7. Interlayered amphibolite and metasedimentary gneisses, including a homogeneous amphibolite with granulite facies-type mafic pegmatites.

8. Layered garnet-bearing amphibolite, probably derived from a gabbroic marginal phase of the anorthosite complex.

9. Leucogabbroic schist.

10. Garnet-bearing Malene metasedimentary gneisses with thin amphibolites.

11. Polyphase, relatively homogeneous, Nûk-type gneisses.

On the island just east of the wharf there are Amîtsoq gneisses with Ameralik dikes and layered basic rocks belonging to the marginal phases of the anorthosite complex. In all of these rocks there is abundant textural evidence of late Archean granulite facies metamorphism, as seen at locality 2.11, although the rocks now have amphibolite facies mineral assemblages. The granulite-amphibolite facies boundary must be within the strongly deformed section through the Nordafar wharf. Elsewhere in this area it can be seen to be tectonic.

**Locality 2.12: Old Færingehavn**

Early Archean rocks intruded by late pegmatites and white gneisses are all affected by very strong "straight belt" deformation. This makes the distinction between early and late Archean rocks rather uncertain, a common situation in this region. There are a number of clearly recognizable Ameralik dikes with abundant plagioclase clots. There are also layered basic rocks that contain granulite facies-type mafic pegmatites. They are thus probably early Archean (Akilia association).

The white gneisses and pegmatites here appear to be the same association as the rocks to the west that are shown as Qôrqt granite on the Buksefjorden 1:100,000 map sheet. These are, however, probably older than the type Qôrqt granite, which post-dates all major ductile deformation. We have been unable to find the thrust shown on the 1:100,000 map sheet. It is drawn through a section where the geology appears to be continuous and where there is an increase in the proportion of pegmatite to white gneiss and a decrease in the intensity of late deformation.

**Locality 2.13: Polarøil**

At this stop we see a typical unit of mid-Archean leucogabbro-anorthosite, a lithology that is widespread throughout the region and forms useful structural markers.

From the west, at the boundary fence of the oil depot, we traverse pegmatite-streaked quartzofeldspathic



gneisses with highly attenuated, migmatized rafts of amphibolite derived from the gabbroic marginal phases of the anorthosite complex. There is no textural evidence to suggest that the gneisses have been retrogressed from granulite facies. Toward the massive leucogabbroic rocks there are discontinuous layers of garnetiferous gneisses that may be metasediments or alternatively may be products of interaction between the metagabbros and the intrusive gneisses.

The anorthositic unit is made up of interlayered, rather fine-grained leucogabbro and anorthosite with subordinate mafic gabbro. All the rocks have probably suffered total metamorphic recrystallization and have been severely flattened and attenuated by straight-belt deformation. This anorthosite locality is situated near the margin of an eye of low strain within the deformation belt. Local graded layering occurs, which indicates that the unit is inverted. This is in accord with the direction of younging observed in the area of lower strain a little to the south.

Table 4. Analyses of Rocks Seen On Excursion 2.

	155734	131490	162475	243057c
SiO <sub>2</sub>	53.06	72.46	61.56	87.80
TiO <sub>2</sub>	2.26	0.24	1.32	0.08
Al <sub>2</sub> O <sub>3</sub>	13.63	14.85	13.89	6.32
FeO <sup>†</sup>	13.54	2.97	8.19	0.10*
MnO	0.20	0.02	na	nd
MgO	2.75	6.94	1.38	0.02
CaO	7.46	0.09	4.26	0.01
Na <sub>2</sub> O	3.07	0.3	3.26	0.61
K <sub>2</sub> O	1.06	0.13	2.87	4.50
P <sub>2</sub> O <sub>5</sub>	0.36	0.03	0.52	0.02
LOI	0.61	0.70	0.43	0.14
Total	98.00	98.73	97.68	99.61
Rb	12	28	105	99
Sr	286	3	148	37
Ba	510	7	145	561
Zn	130	49	na	na
Y	34	185	84	11
Zr	155	545	606	142
Pb	9	2	na	14
Nb	10	60	na	na
Cr	55	25	na	21
Co	37	11	na	na
Ni	15	4	na	nd

na = not analyzed; nd = not detected; \* as FeO.

155734: ferrodioritic gneiss, SE Qilángårssuit

131490: quartz-cordierite gneiss, Sagdlerssua (same unit as that on Simiútat).

162475: Amitsoq augen gneiss, Kanajorssuit.

243057c: quartzite, Simiútá.

### EXCURSION 3

#### NUUK — AMERALIK — NUUK

The eastern contact zone of the "main body" of the Qôrqt granite complex is well seen on the mountains on the north side of Ameralik. Type Amitsoq gneisses with very large rafts of Akilia association basic and other lithologies are cut by a plexus of sub-horizontal sheets of granite and pegmatite. A very thick sheet of layered aplite-pegmatite can be seen capping the eastern end of the mountain Qáqarssuaq. The amount of rafts of country rocks decreases eastwards into the granite, but the sub-horizontal sheeted structure of the complex is still evident.

#### Locality 3.1: Coast Below Inugssugssuaq

Here we will see Amitsoq gneisses in what may be the zone enriched in elements expelled from deeper rocks affected by late Archean granulite facies metamorphism. No specimens from this locality have been analyzed. The rocks have a distinctive pinkish color that is unusual for the region. Most outcrops of Amitsoq gneisses appear grey when viewed from a distance. There are numerous Ameralik dike amphibolites, some strongly broken-up and others more continuous. The gneisses contain granitic layers, both modified early layering and discordant veins, as well as pegmatitic veins bordered by biotite-rich zones. These structures may represent the beginning of melting. The rocks are folded and have a pervasive SSE-plunging fabric element that post-dates granite formation. This linear fabric is not present in strongly discordant pegmatite and granite sheets that are of Qôrqt granite type. The melting episode seen here was thus separated from the intrusion of the Qôrqt granite and pegmatite sheets by the deformation episode that formed the linear fabric. This linear fabric occurs throughout the outer part of Ameralik and may be the same age as the late deformation belt through Nuuk town.

#### Locality 3.2: Nipínganeq

A large body of mafic tonalitic gneiss (analysis 217390, Table 5) occupies the core of a major synform. The central part of the body has been affected by only relatively weak deformation. It does not contain Ameralik dike-type amphibolites and is interpreted as an early phase of the Nûk gneisses.

In exposures on the north coast of Ameralik the tonalitic gneiss has pervasive blebby texture and encloses many big-hornblende pegmatites of the type that elsewhere is seen to have developed during granulite facies metamorphism. These features indicate that the tonalitic gneiss was affected by late Archean granulite facies metamor-

phism, but was later totally retrogressed to amphibolite facies. Intense deformation on both limbs of the synform has erased most textural evidence of granulite facies metamorphism.

Nipínganeq tonalitic gneiss crops out east of the unit of early Archean rocks on Kangimut sangmissoq and in a very attenuated state just outside the leucogabbroic "membrane" of the Inugssugssuaq structure (see Locality 3.4). In these areas too, there is abundant textural evidence that it has been retrogressed from granulite facies. Metamorphosed tabular bodies of amphibolite of Ameralik dike type are absent.

The tonalitic gneiss is cut by many irregular, composite bodies of pegmatite-granitic gneiss that post-date granulite facies metamorphism. They were emplaced along active movement zones and developed a primary gneissic structure as they crystallized. Six samples yielded a Rb/Sr whole rock isochron age of  $2692 \pm 62$  Ma with  $Sr_i = 0.7060 \pm 0.0015$  (Roberts, 1979). The youngest rocks in these exposures are sub-horizontal pegmatite sheets belonging to the Qôrqut granite complex.

Four specimens of the tonalitic gneiss yielded a Rb/Sr whole rock isochron age of  $2514 \pm 50$  Ma with  $Sr_i = 0.7028 \pm 0.0005$  (Roberts, 1979). This cannot be the age of intrusion of the tonalite and is interpreted as the result of Rb introduction associated with the intrusion of the Qôrqut granite complex. It is probable that the tonalite had been depleted in Rb during granulite facies metamorphism.

### Locality 3.3: Kangimut sangmissoq

This is the most controversial, but perhaps also the most important locality to be visited during the workshop. Rocks that have clearly been retrogressed from (late Archean) granulite facies have the field characteristics of early Archean Amîtsoq gneisses and Ameralik dikes. However the gneisses have Rb/Sr, Pb/Pb and Sm/Nd characteristics that are considered by Jones, Moorbath and Taylor (this volume) to indicate derivation from a mantle source in the late Archean. We consider that these gneisses are dominantly early Archean in age and that the isotopic systems in them were severely disturbed during late Archean granulite facies metamorphism.

The locality (Fig. 26) is near the eastern edge of a unit of Amîtsoq-type gneisses that lies within the core of the same broad, south- to southeast-plunging synclinorium as the Nipínganeq tonalitic gneiss. Nipínganeq (Nûk) tonalitic gneiss crops out on the coast to the east, only a short distance across strike. Both the Nûk tonalitic gneiss and the gneisses at this locality have pervasive blebby texture. Throughout the Kangimut sangmissoq unit the gneisses enclose abundant tabular bodies of amphibolite

of Ameralik dike type. A number of these amphibolites contain trains or scattered clots of calcic plagioclase. There can be little doubt that these amphibolites are derived from basic dikes indistinguishable from the type Ameralik dikes, but their original discordant relations to the gneisses have been erased by deformation and subsequent recrystallization under granulite facies conditions. Mafic pegmatites are common within the amphibolites. Toward the northern end of the outcrop there is a 20-25-m-thick body of well-layered basic rock that has a 2-m-thick zone with abundant large plagioclase clots. Relic cores in this body preserve granulite facies mineral assemblages (specimen 152765, Table 2 and Fig. 4 in Griffin et al., 1980). We interpret this body as an unusually thick Ameralik dike. Thick Ameralik dikes with similar layering have been observed elsewhere in the region.

A number of the metamorphosed basic dikes have been migmatized along their contacts, but are still continuous. Others have been split into sub-parallel slices by granitic material emplaced parallel to their margins. Locally the dikes have been completely broken up and occur as separated fragments "floating" in the gneisses. Amphibolites derived from basic dikes are completely absent from the Nûk tonalitic gneiss to the east.

The gneisses in the Kangimut sangmissoq unit are variable, coarse-textured and nebulitic. In places the mafic spots that give the blebby texture are open clusters of coarse-grained biotite, garnet, hornblende and opaque minerals. Elsewhere they are polygranular aggregates of hornblende with a little biotite. The gneisses are tonalitic to trondhjemitic in composition (analyses 152755, 152757, Table 3; see also Nutman et al., this volume). They contain little-deformed big-hornblende pegmatites, in some of which the large hornblendes have cores of cummingtonite and quartz that locally contain relic orthopyroxene.

The migmatization and break-up of some of the metamorphosed basic dikes shows that the gneisses must contain some material that is post-basic dike, but pre- or syn-granulite facies metamorphism. Recrystallization under granulite facies conditions (textural homogenization) has blurred or erased contacts between this material and the earlier gneisses. It is thus quite possible that the samples used for isotopic studies include some Nûk material. However, the abundance of relatively unbroken amphibolites of basic dike type, which is comparable to the abundance of Ameralik dikes in typical unmigmatized Amîtsoq gneisses elsewhere, indicates that the gneisses here must be dominantly older than the basic dikes.

Thin, composite dikes and veins of granitic gneiss and pegmatite post-date the granulite facies metamorphism and were intruded along movement zones. Four specimens give a Rb/Sr whole rock isochron age of  $2680 \pm 180$

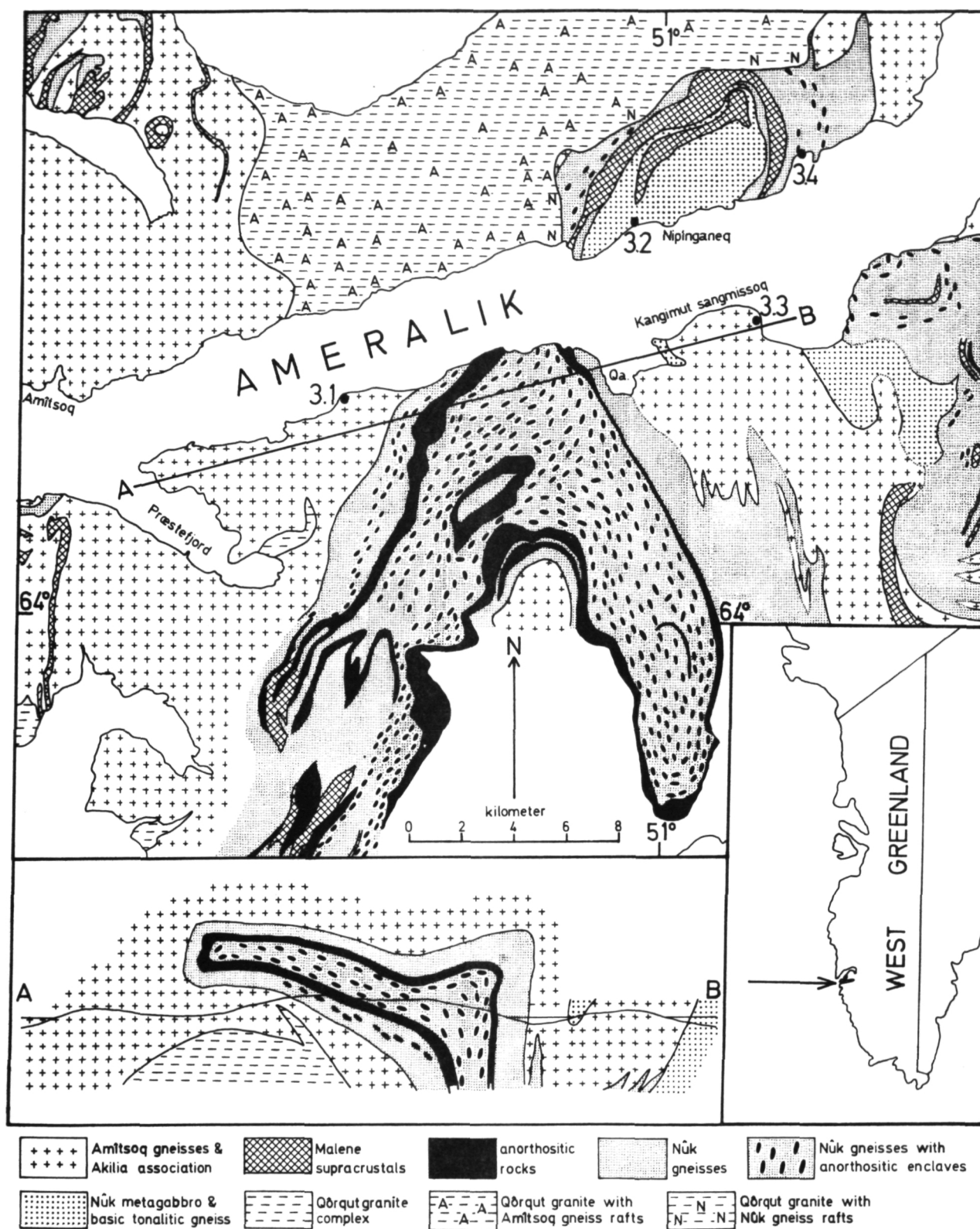


Fig. 26. Geological sketch map of central Ameralik.

Ma with  $Sr_i = 0.7045 \pm 0.0010$  (S. Moorbath, pers. comm.). The field and isotopic characters of these dikes indicate that they are the same generation as the late, composite dikes that cut the Nipínganeq tonalitic gneiss at the last locality. A rusty layer about half-way along the outcrop, composed of plagioclase, quartz and pale brown mica with smaller amounts of sulphides, sphene, epidote and apatite, may be a late intrusive sheet.

Suites of specimens were collected as Amítoq gneisses retrogressed from granulite facies by V.R.M. and Dr. Stephen Moorbath from this locality and from the western part of the same Amítoq gneiss unit at Qasigiánguit, as well as from the tonalitic Nûk gneiss to the east, in 1976 and 1977. Isotopic results are reported for these specimens by Jones, Moorbath and Taylor (this volume).

1. Rb/Sr: Six gneisses retrogressed from granulite facies define a  $2770 \pm 185$  Ma isochron with  $Sr_i = 0.70195 \pm 0.00054$ .

2. Pb/Pb: The pattern of Pb isotopes in 18 samples is analogous to the pattern in Nûk gneisses within the belt through Godthåbsfjord that was not affected by late Archean granulite facies metamorphism (Taylor et al., 1980). The Kangimut sangmissoq gneisses show evidence for contamination with Amítoq-type Pb, but few show severe contamination effects, and most have a very large proportion of their initial Pb from a juvenile source at ca. 2770 Ma.

3. Sm/Nd: Six gneiss samples define a  $2825 \pm 125$  Ma isochron with  $\epsilon_{Nd(1)} = +2.2$ .

Rb/Sr and Sm/Nd data on a further suite of gneisses collected from this unit in 1980 are reported by Collerson et al. (this volume).

Zircons from a single gneiss specimen from this locality have been analyzed by Professor H. Baadsgaard (pers. comm.). The datum point lies on the lower part of the same discordia line on a U/Pb plot as Akilia association zircons (Baadsgaard et al., 1984). Akilia zircons that plot near the lower end of this discordia line are from outcrops close to the main body of the Qôrqt granite complex, the eastern contact of which is only 5 km from this locality. The  $^{207}\text{Pb}/^{208}\text{Pb}$  age is 2830 Ma.

The field evidence that the rocks at this locality are dominantly early Archean Amítoq gneisses is:

1. The presence of abundant bodies of amphibolite identical to Ameralik dikes in the type Amítoq gneisses only 10 km to the west of this unit. It is most unlikely that these could be intra- or post-Nûk dikes since comparable dikes are completely absent from adjacent Nûk gneiss units, including the Nipínganeq tonalitic gneiss.

2. The continuity of the geology from the type Amítoq gneisses in outer Ameralik and Præstefjord, which

preserve early Archean isotopic characteristics, through the whole length of Ameralik and east as far as our personal knowledge of the geology extends.

Throughout this section Amítoq gneisses, like those at this locality, alternate with units of younger rocks from which Ameralik dike-type amphibolites are absent. A structural reconstruction (Fig. 26, cross section; see also locality 3.4) indicates that the Kangimut sangmissoq gneisses are the same major unit as the type Ameralik gneisses in outer Ameralik.

#### Locality 3.4: Naujánguit

At this locality we see post-granulite facies, granodioritic gneisses with enclaves of anorthositic lithologies.

On the south side of Ameralik the type Amítoq gneisses are separated from the Kangimut sangmissoq unit by Nûk gneisses that enclose two continuous units and abundant enclaves of anorthositic rocks. Stainforth (1977) and Chadwick et al. (1982) interpreted this as a major magmatic nappe structure, the Inugssugssuaq (Inussus-suaq in the new orthography) nappe, in which a "membrane" of anorthositic rocks was blown up like a balloon by granodioritic Nûk magmas that crystallized to form the gneisses with abundant anorthositic enclaves in the core of the structure. The hinge of the nappe is not exposed in the ground mapped by Stainforth, but was considered to be exposed within the late deformation belt north of the mouth of Buksefjorden. Graded igneous layering in the anorthositic units faces outwards in opposite directions on the limbs of the structure, indicating an isoclinal fold. Stainforth's interpretation of the structure is incorporated into the cross section in Fig. 26. We have reservations about this interpretation and consider it even possible that the granodioritic gneiss was intruded as a thick sheet into the anorthositic unit *after* it had been isoclinally folded. The same unit of granodioritic gneiss with abundant anorthositic enclaves appears to extend from south of Færingehavn through central and inner Ameralik and into Godthåbsfjord at least as far as the northern part of Storø.

The lithologies of the Inugssugssuaq structure extend across Ameralik, are folded around the Nipínganeq synform, and reappear on the coast at Naujánguit. There is no blebby texture or other evidence of previous granulite facies metamorphism in the granodioritic gneiss with anorthositic enclaves here or in the core of the Inugssugssuaq structure. We conclude that the granodiorite was intruded after the late Archean granulite facies metamorphism, and that the Inugssugssuaq structure and the open folds that re-fold it, including the Nipínganeq synform, are thus also post-granulite facies.



Table 5. Analyses of Rocks Seen On Excursion 3.

	217390	152755	152757
SiO <sub>2</sub>	62.70	66.54	69.02
TiO <sub>2</sub>	0.60	0.65	0.38
Al <sub>2</sub> O <sub>3</sub>	16.50	16.02	15.52
FeO <sup>i</sup>	5.54	4.45	3.30
MnO	0.09	na	na
MgO	2.25	1.39	0.95
CaO	5.62	5.13	4.20
Na <sub>2</sub> O	4.40	3.85	3.99
K <sub>2</sub> O	0.85	0.43	0.94
P <sub>2</sub> O <sub>5</sub>	0.14	0.12	0.08
LOI	na	0.63	0.56
Total	98.69	99.21	98.94
Rb	15		
Sr	236		
Zn	64		
Y	13		
Zr	152		
Co	44		
Ni	24		

na = not analyzed.

217390: tonalitic gneiss, Nipínganeq (Roberts, 1979).

152755, 152757: Kangimut sangmissoq gneisses.

## EXCURSION 4

## NUUK — QÔRQUT

Localities for Excursion 4 are shown in Fig. 27.

## Locality 4.1: Máluto

At this stop we will see rocks affected by 3000-2950 Ma granulite facies metamorphism on the east coast of Nordlandet.

On the north coast of the sound between Máluto island and the mainland we see gneisses that are only partly retrogressed from granulite to amphibolite facies. In the retrogressed gneisses, note that there is little blebby texture of the type seen in gneisses retrogressed from early Archean and from ?2800 Ma granulite facies in the southern parts of the region. However there are abundant mafic pegmatites and ultramafic segregations in rafts of mafic rocks. The granulite facies rocks are cut by a sheet of pale weathering, streaky, granodioritic gneiss, one of the Kanásut sheets of Reed (1980). The granodioritic gneiss does not have or appear to have had granulite facies mineral assemblages, yet there is no indication that it retrogressed the granulite facies rocks that it cuts. We suggest that it was intruded under granulite facies conditions, but contained sufficient water to prevent it crystallizing to a granulite facies assemblage. It may be

the product of partial melting under granulite facies conditions in which the granodioritic magma scavenged water from the enclosing rocks.

There has been extensive retrogression to amphibolite facies of rocks in the surrounding outcrops, which weather whitish. In most places the retrogression was static, but locally it appears to have been accompanied by deformation, possibly of the same age as the deformation in the late belt through Nuuk town and the western part of Sadleø and Bjørneøen.

## Locality 4.2: Qârusup imá

A broad arching structure can be seen on the south-western part of Bjørneøen. This is one of a row of domal antiforms that includes the Lille Malene antiform (excursion 1). The core of the structure is composed of homogeneous granodioritic gneiss. The western limb of this fold follows the edge of the late deformation belt that extends through Nuuk town.

At the locality visited, the coarse-textured granodioritic gneiss is cut by irregular bodies of finer-textured trondhjemitic gneiss. The contact relations are best seen when the rocks are wet. This was the first locality where V.R.M. noticed discordant, intrusive relations between different gneiss phases, when he and his assistant were sitting on this exposure drying off after a swim in 1966. Earlier that summer he and Professor John Sutton had been shown the section of polyphase Nûk gneisses with rafts of Malene amphibolites and chlorite-rich ultramafic rocks on the coasts of the sound between Bjørneøen and Sadleø. They were told (and they believed) that the gneisses were metasediments derived from greywackes and arkoses interbedded with metavolcanic chlorite schists.

However, nobody is infallible. The trondhjemitic gneiss at this locality was considered by V.R.M. and A.P.N. in 1980 to be a Qârusuk dike (see locality 4.3). We were surprised when zircons from it proved to lie on a 2880 Ma discordia line (specimen 248079, Baadsgaard and McGregor, 1981), showing that it belongs to the type Nûk gneisses. Zircons from the granodioritic gneiss (248078) lie on a 2890 Ma discordia line. An analysis of the granodioritic gneiss (163275) is given in Table 6 and a REE pattern for the same specimen in Fig. 28.

On both sides of this outcrop the gneisses are affected by zones of strong deformation in which intrusive relations have been lost and the granodioritic and trondhjemitic phases have become concordant layers in a regularly layered sequence. In this state of deformation, which is more characteristic of the region than the low deformation areas where discordant relations are preserved, the Nûk gneisses could well be taken to be derived from a layered sedimentary sequence.

#### Locality 4.3: South-East Corner of Bjørneøen

Malene supracrustal amphibolites and ultramafic rocks intruded by polyphase Nûk gneisses with late Archean Qârusuk aplitic dikes. This area lies within a belt where the metamorphic grade is lower than elsewhere in the region and the Malene and Nûk rocks are unusually fine-grained. Primary features in all lithologies are better preserved than elsewhere in the region with the exception of the Ivisârtoq and Isukasia areas.

The thick Malene supracrustal unit is made up of variable amphibolites and ultramafic rocks. Around the point to the east there is a very small area with relic conglomeratic (agglomeratic) structure and areas with deformed pillow breccia and pillow lava structures (analysis 131501, Table 7). The western part of the Malene unit is made up of green ultramafic lithologies rich in tremolite and magnesian chlorite. Locally this lithology has relic structures suggesting pillow lavas. The composition (analyses 152771, 152772, Table 7) is very similar to that of Malene komatiitic pillow lavas on Ivisârtoq (Hall, 1980).

The supracrustal unit contains lenses of brown-weathering, olivine-bearing ultramafics. Larger bodies of similar lithologies are abundant in the gneisses to the west.

On the coast west of the supracrustal unit are some of the best outcrops of Nûk gneisses in the region. There is a considerable variety of lithologies that range in composition from dioritic to trondhjemitic, with grey, tonalitic types most abundant. Intrusive relations between gneisses and rafts of supracrustal amphibolite and ultramafic rocks and between Nûk gneiss phases are commonly preserved. An analysis of typical tonalitic gneiss (163222) from these outcrops is given in Table 6 and its REE pattern in Fig. 28. A sample of the dominant tonalitic gneiss (248087) has given a zircon U/Pb concordia intercept date of 3070 Ma (Baadsgaard and McGregor, 1981).

The Nûk gneisses are cut by irregular dikes of fine-grained, greenish-grey aplite belonging to the Qârusuk dikes (McGregor et al., 1983), for which this is the type locality. One of the Qârusuk dikes at this locality has given a U/Pb zircon concordia intersection date of 2660

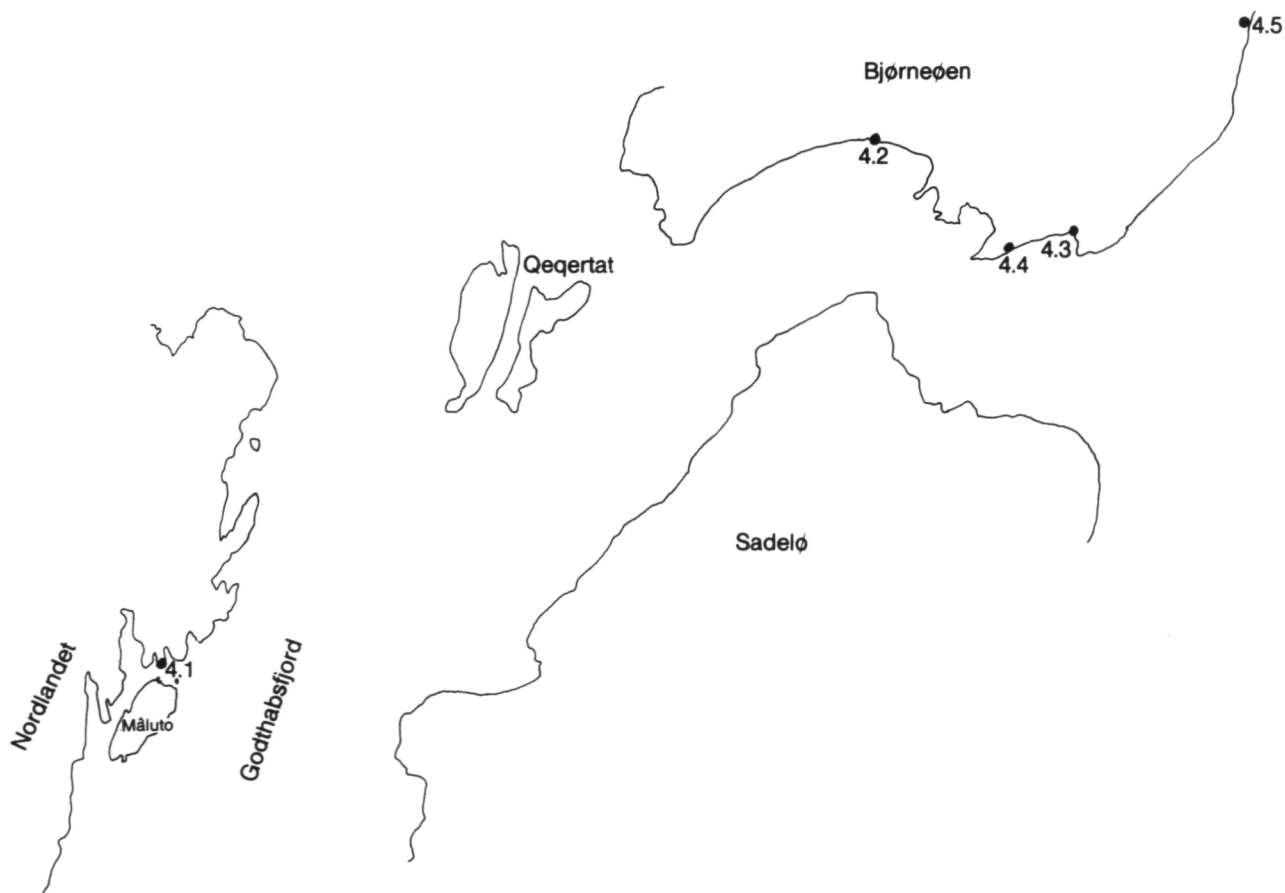


Fig. 27. Locality map for excursion 4.

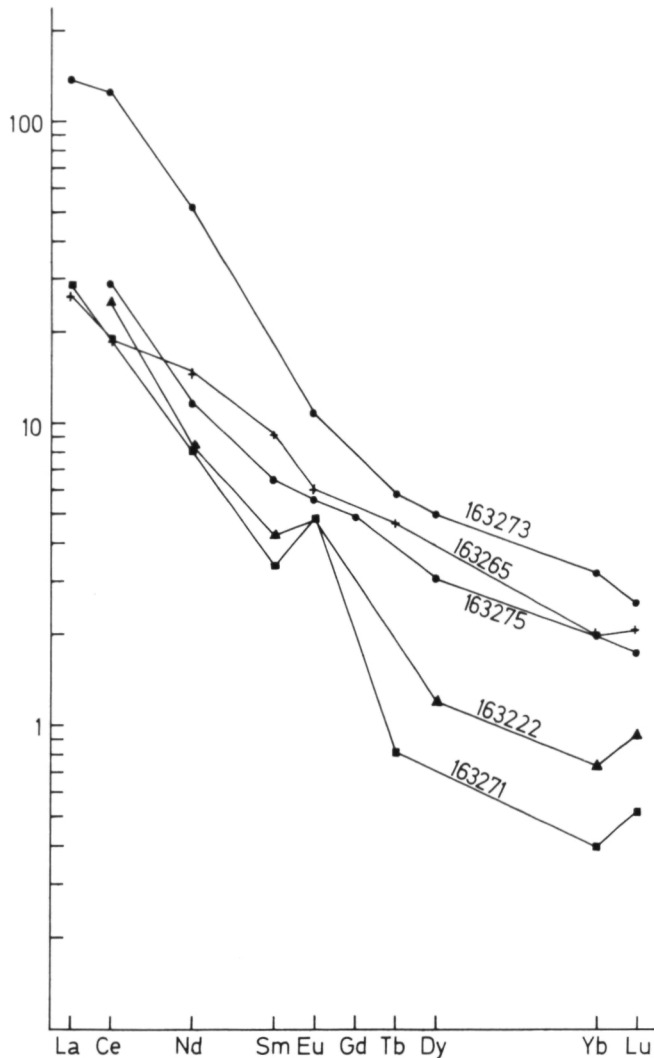


Fig. 28. REE patterns for Nûk gneisses and a Qârusuk dike, southern Bjørnefæn. Unpublished data from Dr. J.G. Arth, U.S.G.S., Reston.

Ma (Baadsgaard and McGregor, 1981). An analysis of this dike (163273) is given in Table 6 and its REE pattern in Fig. 28. The Qârusuk aplites are finer-grained than the Nûk gneisses they cut. A number of features indicate that they were intruded into active movement zones. Steps in the dike contacts extend out into the country rocks as shear zones. Cataclastic structures occur along some dike margins. Some dikes contain quartz veins with the form of tension gashes. The margins of the least deformed dikes have a bleached appearance that is attributed to movement of fluids along the movement zones into which the Qârusuk magmas were intruded.

Qârusuk dikes from this area (86523, 86536, 86550) were included in suites of Nûk gneisses considered by

Moorbath and Pankhurst (1976) and Taylor et al. (1980; 1984). They have much larger proportions of Amitsoq-type component in their Pb compared with the enclosing Nûk gneisses and  $T_{\text{CHUR}}^{\text{Nd}}$  model ages of 3200-3660 Ma, suggesting that their source included a significant component of Amitsoq gneisses or that the magmas or fluids that migrated along the same fractures scavenged Pb, Nd (and Sr) from Amitsoq gneisses that they passed through.

The Qârusuk aplites appear to be contemporaneous with the very large muscovite-garnet-bearing pegmatites that can be seen in this area. They are assumed to be the same generation as the large pegmatites that cut the Malene unit on Sadleø and Store Malene (excursion 1).

#### Locality: 4.4

On the west side of the bay from locality 4.3, Nûk gneisses are more strongly deformed and intrusive relations are less well preserved. Rafts of Malene amphibolite and ultramafic rocks are cut by several generations of Nûk and Qârusuk veins that deformed more competently than the mica- and chlorite-rich Malene rocks. This resulted in complex interference patterns that may not have much regional significance.

#### Locality 4.5: Naqerdloq kitledq

On the southeast coast of Bjørnefæn, the Malene amphibolite is structurally underlain by a thick sheet of homogeneous Nûk granodioritic gneiss that can be followed south over eastern Sadleø and along the eastern face of Store Malene. Intrusive relations to the Malene amphibolite are seen as steps in the slightly transgressive contact.

A suite of 11 samples from coastal outcrops of this unit between Ivînguit and Naqerdloq kitledq defines a Rb/Sr whole rock isochron with an age of  $2980 \pm 50$  Ma and  $Sr_i = 0.7022 \pm 0.0003$ , and a Pb/Pb whole rock isochron age of  $3020 \pm 260$  Ma. The Pb/Pb whole rock isochron is not perfect, but indicates that this unit was "not grossly heterogeneous with respect to initial Pb isotopic composition" (Taylor et al., 1980). An analysis (163265) and a REE pattern are given in Table 4 and Fig. 28.

#### Locality 4.6: South Coast of Storø

The western intrusive contact of the Qôrqt granite complex is well exposed on the mountain face on the southern end of Storø (Fig. 29). The country rocks comprise Amitsoq gneisses enclosing a unit of black Malene amphibolite. The Malene rocks are broken up by sheets of pale granite that form a sub-rectangular network. This relationship suggests that the rocks into which the Qôrqt granite was intruded acted in a brittle

manner. Few sheets of granite penetrated through the Malene amphibolite into the Amîtsoq gneiss unit to the west. At the very top of the 1000 m cliff, the remains of a unit of Amîtsoq gneisses can be seen east of the Malene unit. Rafts of Amîtsoq gneiss can be discerned as grey, tabular blocks within the paler granite. These rafts have been wedged inwards by granite intruded along their foliation surfaces and thus resemble stoped blocks.

At the base of the cliff the granites comprise both leucocratic and grey granites and contain many locally derived rafts of Amîtsoq gneisses that enclose Ameralik dikes. Some of the leucocratic granite sheets are schlieric and contain a few highly modified gneiss enclaves which are interpreted to have been brought in from the melting zone.

#### Locality 4.7: Qôrqt Hotel

The hotel is situated near the eastern contact of the Qôrqt granite complex. Qôrqt granite with enclaves of country rocks, largely Amîtsoq gneisses, forms the sheer

face of the mountain Qajûta which can be contemplated through the dining room windows. On the 1530 m. mountain NNE of the hotel, sheets of group 3 granites can be seen fingering out laterally into the country rocks. The intermediate and upper zones of the complex (Fig. 11) can be seen on the mountains north of the hotel on the western side of the U-shaped valley of Nigsik.

Table 6. Analyses of Nûk gneisses and a Qârusuk dike from southern Bjørnefæn.

	163222	163271	163275	163265	163273
SiO <sub>2</sub>	69.16	72.14	72.20	72.68	71.37
TiO <sub>2</sub>	0.28	0.11	0.20	0.15	0.33
Al <sub>2</sub> O <sub>3</sub>	17.06	16.01	14.92	14.83	14.74
Fe <sub>2</sub> O <sub>3</sub>	0.43	0.07	0.32	0.31	0.25
FeO	1.27	0.76	1.11	0.72	1.64
MnO	0.01	0.02	0.03	0.03	0.02
MgO	0.73	0.29	0.46	0.34	0.47
CaO	3.41	2.65	2.21	2.12	1.80
Na <sub>2</sub> O	5.34	5.50	5.09	4.74	4.14
K <sub>2</sub> O	1.72	1.76	2.35	2.77	4.12
P <sub>2</sub> O <sub>5</sub>	0.04	0.02	0.04	0.04	0.13
LOI	0.43	0.30	0.41	0.49	0.47
Total	99.88	99.63	99.34	99.22	99.48

163222: Dominant grey, tonalitic Nûk gneiss, bay west of Sitdlisit nûat, south-east Bjørnefæn, 64° 21.7'N, 51° 20.0'W.

163271: Pale, trondhjemitic gneiss sheet, 2 m. thick, cutting grey, tonalitic Nûk gneiss, Qingordlit, south Bjørnefæn 64° 21.7'N, 51° 21.8'W.

163275: Homogeneous, granodioritic Nûk gneiss in core of antiform, Qârusup imâ, south Bjørnefæn 64° 22.7'N, 51° 24.0'W.

163265: Homogeneous, granodioritic Nûk gneiss, southeast coast of Bjørnefæn between Ivinguit and Naqerdloq kitdleq, 64° 23.9'N, 51° 15.2'W.

163273: Qârusuk aplitic dike cutting folded Nûk grey gneiss, Qingordlit, south Bjørnefæn, 64° 21.7'N, 51° 21.8'W.

## EXCURSION 5

### QÔRQT

This excursion is planned to give people the opportunity to stretch their legs and get some feeling of what it is like to do field work on foot in this region. We walk along the coast between the two streams at the head of Qôrqt fjord.

The rocks are a little outside the eastern margin of the Qôrqt granite complex and comprise Amîtsoq gneisses with Ameralik dike amphibolites and rafts of Akilia association, cut by Qôrqt granite and pegmatite. There is relic blebby texture especially in the more mafic Amîtsoq gneisses and in migmatized Akilia rocks, suggesting that these rocks have been retrogressed from granulite facies. There are no indications of previous granulite facies metamorphism in the relatively unbroken Ameralik dikes. This suggests that the Amîtsoq gneisses in this area were affected by early Archean granulite facies metamorphism before intrusion of the Ameralik dikes.

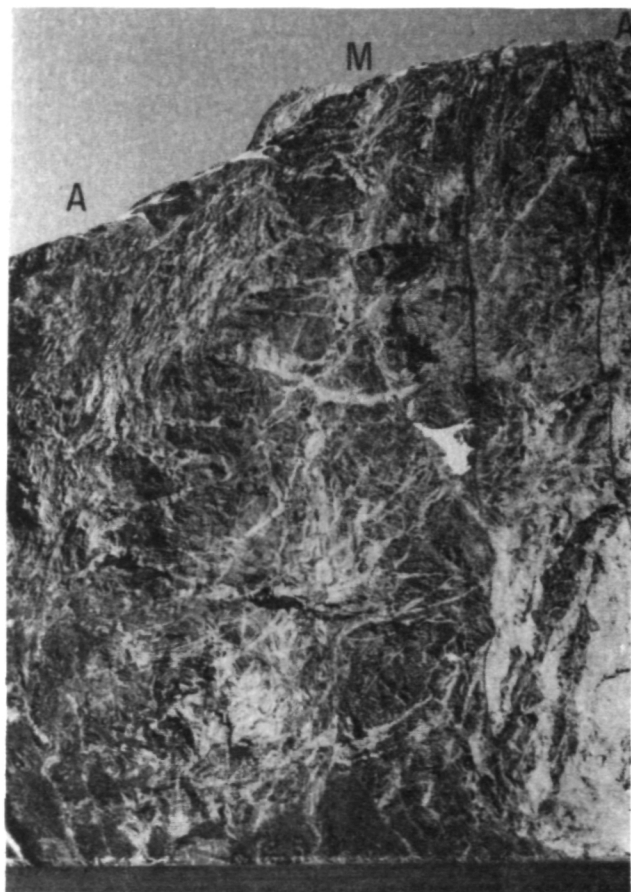


Fig. 29. Intrusive contact of the Qôrqt granite complex on the southern end of Storø. Amîtsoq gneisses are labelled A and Malene amphibolite M.



Amitsoq gneisses in the first outcrops contain fragments of Ameralik dike amphibolites and enclaves of Akilia ultramafic rocks with zoned reaction rims against the gneisses. Gneisses rich in biotite and hornblende may have been contaminated with material from Akilia ultramafic rocks. Qôrqt lithologies include biotite-magnetite-bearing pegmatites and composite aplite-pegmatite sheets.

On the point about half-way along the outcrop there is a well-layered sequence of Akilia association rocks, mainly amphibolite with hornblende-clinopyroxene rock, skarn-quartzite and garnet-bearing layers. A discordant body of very dark green rock is probably an ultramafic Ameralik dike. It is in turn cut by a deformed granitic dike of Qârusuk type. The Akilia lithologies have mafic segregation pegmatites of the type formed in basic rocks during granulite facies metamorphism.

Table 7. Analyses of Malene supracrustal basic and ultrabasic rocks from Sîdlisî nûat, Bjôrneføen, and Ivisârtoq.

	131501	152771	152772	207625
SiO <sub>2</sub>	51.47	47.02	43.04	46.49
TiO <sub>2</sub>	2.48	0.33	1.29	0.55
Al <sub>2</sub> O <sub>3</sub>	14.44	9.48	8.62	9.37
FeO	11.75	10.80	12.35	11.16
MnO	0.21	0.21	0.20	0.23
MgO	2.50	16.23	14.49	17.05
CaO	8.75	11.80	12.92	11.96
Na <sub>2</sub> O	4.5	1.45	1.70	2.03
K <sub>2</sub> O	0.89	0.07	0.20	0.02
P <sub>2</sub> O <sub>5</sub>	0.44	0.18	0.25	ND
LOI	0.37	0.90	2.80	—
Total	97.80	98.47	97.86	98.96
Rb	23	2	1	9
Cu	600	53	100	
Sr	419	66	140	37
Ba	730	7	13	
Zn	110	88	125	81
Y	30	9	17	9
Zr	189	16	67	28
Pb	19	2	—	
Nb	13	2	7	1
Cr	110	2449	2641	1765
Co	46	65	68	
Ni	87	500	607	556

131501: Amphibolite with possible relic pillow-lava structure, Sîdlisî nûat.

152771, 152772: Green tremolite-chlorite rock with possible relic pillow-lava structure, Sîdlisî nûat.

207625: Komatiitic metavolcanic rock from sequence of pillow-structured and associated homogeneous flow amphibolites, Ivisârtoq (Hall, 1980; Friend et al., 1981).

131501, 152771, 152772: Leeds University XRF analyses.

On the last point where the coast turns into the bay with the second stream there are clearly discordant Ameralik dike amphibolites that cut gneisses with spotty pegmatites of the type found elsewhere in rocks known to have been retrogressed from granulite facies. There are small enclaves of Akilia hornblende-clinopyroxene rock.

From here one can return to the hotel along the coast or by climbing up the northern branch of the stream and then either traversing obliquely back down to the coast or continuing up over a 600 m-high ridge and then down to the Nigsik valley.

The basic unit that crops out in the stream above Qíngua was mapped as Malene supracrustals, but we now think it more likely to be an unusually large unit of Akilia association. It contains thin layers of magnetite- and clinopyroxene-bearing quartzites, which are typical Akilia lithologies not observed in Malene basic units. It also contains mafic segregation pegmatites like those seen in the Akilia unit on the coast and several layers of massive amphibolite that may well be concordant Ameralik dikes. Pale grey, talc-bearing ultramafic rocks with grey, asbestiform amphibole are associated with the unit.

On the slope between the stream and the top of the 600 m ridge there is a thick basic unit with large ultramafic bodies that is mapped as Akilia association.

From the top of the ridge one descends into the Nigsik valley through the same unit of Amitsoq gneisses as crops out on the coast traversed earlier in the day. Along the stream in the valley, Qôrqt granite and pegmatite sheets alternate with Amitsoq gneisses containing rafts of various Akilia lithologies including quartz-magnetite ironstones, hornblendite and other ultramafic and mafic rocks. They are cut by clearly discordant Ameralik dikes.

For those who return early to the hotel, there are pleasant and interesting walks along the coast to the west where there are good exposures of Qôrqt granite that, especially to the west, encloses rafts of Amitsoq gneisses and ultramafic rocks, or up the stream behind the hotel, where the rocks are those mentioned in the last paragraph.

## EXCURSION 6

### QÔRQUT - NUUK

Localities for Excursion 6 are shown in Fig. 30.

#### Locality 6.1: Rockfall at Ujará

This locality shows partial melting of Amitsoq gneisses and the production of group 1 granites. It is in the lower zone of the Qôrqt granite complex and consists of inhomogeneous, polyphase granite containing many enclaves of modified Amitsoq gneiss.

At Ujarâ the whole process of partial melting may be demonstrated and some idea of the conditions under which this melting took place may be obtained. Given the mineral assemblages of the pegmatite-banded Amîtsoq gneisses and the granitic product, partial melting took place under a maximum of mid-amphibolite facies conditions. Enclaves of slightly modified Amîtsoq gneiss (mesosome) may be found progressively changed into a banded metatexite with granitic, hypidomorphic granular-textured felsic layers (leucosome) separated by biotite-rich layers (melanosome). A range of these textures and structures is shown in Figs. 12 and 13. With an increase in the volume of granitic material, fluid turbulence occurred and the metatexite became disrupted, resulting in the formation of inhomogeneous diatexite. This comprises leucocratic granite containing schlieren of biotite and enclaves of metatexite that were undergoing disaggregation.

At this locality there is good evidence for the formation of small batches of inhomogeneous granite, and hence an explanation for the polyphase nature of the complex. There was little mixing of the liquids that were produced partly because of the small volume of each batch, and partly because of thermal and viscosity contrasts. The inhomogeneity of the leucocratic granite is the result of disruption and incorporation of melanosome into the liquid. Disaggregation of the schlieren, or their smearing out to form biotite lamellae can also be seen, suggesting that much of the biotite in the granite could be derived

from the parent gneisses. Layering in the leucocratic granite has several origins. Most commonly it is an alternation of slightly different granitic lithologies, often separated by biotite lamellae. These may have been different batches of liquid that are contained within a biotite membrane and that have been attenuated by shear, or a biotite lamella may have been exploited as a line of weakness by an intrusive sheet.

The cliffs of the mountains to the north-northwest and on the opposite side of Ûmánap suvdlua show the intermediate zone of the Oôrqut granite complex, composed mainly of group 2 grey granites and enclaves of country rocks. The tops of the mountains are in the upper zone that is made up of group 3 composite granite sheets separating lozenge-shaped rafts of country rocks.

#### Locality 6.2: South-East Corner Of Storø

This locality is in the lower zone of the Oôrqut granite complex. Group 1 leucocratic granites contain enclaves of Amîtsoq gneisses and associated lithologies. A few enclaves have been carried into this part of the granite from parts of the complex where granite formation had taken place, while the majority are unmodified and therefore probably locally derived.

The enclaves at locality 6.1 are thought to have been brought in a short distance from the melting zone. To the north-east across the fjord, under Qáqarssuaq on the south side of the mouth of Oôrqut, Nûk gneisses (which contain enclaves of anorthositic rocks) show evidence of

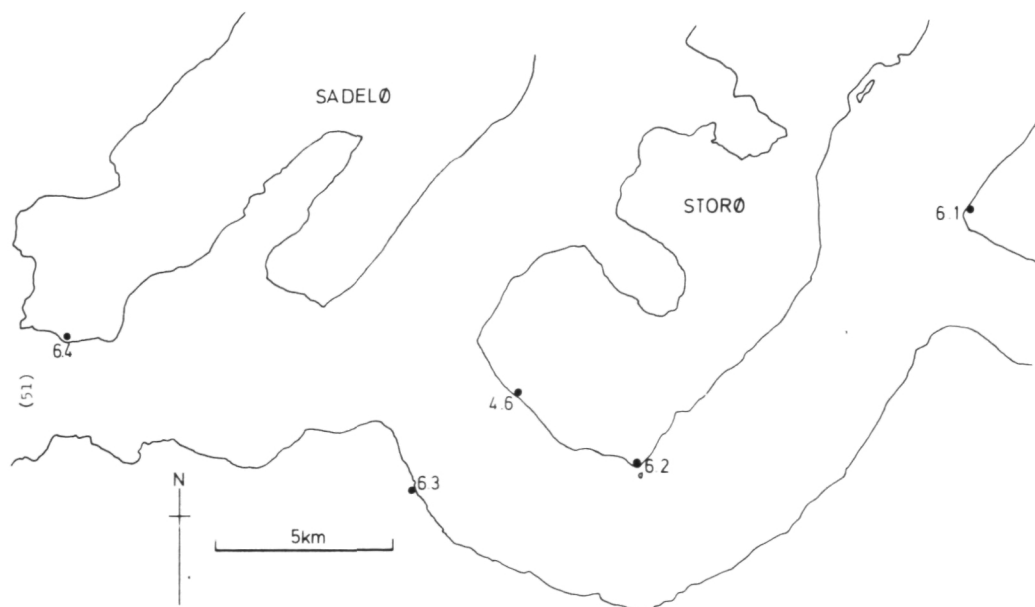


Fig. 30. Locality map for excursion 6.

arrested partial melting. Because of the extent of this outcrop it is considered that these rocks are probably *in situ* and thus are part of the melting zone.

The contact zone of the Qôrqt granite complex on the south side of the fjord is poorly exposed (by Greenland standards) because of lichen and algae that grow on the moist, north-facing rock faces. The exposures of Amîtsoq gneisses to the west are better and give a good impression of the density of Ameralik dike amphibolites in typical Amîtsoq gneisses. The thin unit of Malene amphibolite with bodies of ultramafic rocks is the same as the unit seen at the contact of the Qôrqt granite on the south coast of Storø.

### Locality 6.3:

A thin, folded Ameralik dike that contains plagioclase clots is clearly discordant to layering in Amîtsoq gneisses on ice-polished slabs (careful, they are slippery!). It may be an apophysis of the thick, massive Ameralik dike exposed a little farther along the coast to the west.

### Locality 6.4: South-West Coast Of Sadelø

The same unit of Amîtsoq gneisses strongly penetrated by Nûk gneisses as on the Nuuk peninsula around and east of the airport. The gneisses enclose many bodies of Ameralik dike amphibolite, some sub-continuous and others broken up, that are veined by gneiss and pegmatite. Several of the Ameralik dikes have clots of calcic plagioclase. The rocks are in the core of a synform and have a strong linear fabric with variable plunge.

On the steep coast to the west, many large, highly broken-up and migmatized Ameralik dikes can be seen as we sail past.

In these rocks it is very difficult to collect a sample of early Archean Amîtsoq gneiss that one can be sure does not contain any later material. We have generally avoided this type of geology in our collecting for isotopic and other studies.

Early Archean rocks in the south-eastern part of the region are commonly as strongly penetrated by younger material as those seen at Locality 6.4. In addition, however, they have suffered textural homogenization, like that seen in the gneisses at Kangimut sangmissoq, during recrystallization under granulite facies conditions. The resulting blebby textured gneisses, in which it is very difficult or impossible to distinguish the early Archean component from later material, remind V.R.M. of some of the outcrops he has seen in the Minnesota River Valley. Where, as is commonly the case, the texturally homogenized gneisses have been further deformed and intruded by later granitoids, recognition of an early Archean component becomes virtually impossible.

Table 8. Chronological sequence of events in the Godthåbsfjord - Ameralik - Færinghavn Region.

Age	Event
57 Ma.	Intrusion of "red dikes" around the mouth of Ameralik.
ca. 1150 Ma.	Mild thermal event shown by fission track ages.
1500-1600 Ma.	Metamorphism and metasomatism that caused partial recrystallization and is recorded in Rb/Sr mineral ages.
2000-1800 Ma.	Intrusion of basic dikes ( <i>MD dikes</i> ), faulting with retrogression under greenschist facies conditions.
ca. 2550 Ma.	Intrusion of post-tectonic granites and pegmatite sheets at ( <i>Qôrqt granite complex</i> ).
2700-2600 Ma.	Ductile deformation under amphibolite facies conditions. Formation of linear belts of intense deformation and elongate basins and domes. Intrusion of granitoid sheets (including the <i>Qârusuk dikes</i> ).
2800 Ma.	High-grade metamorphism that reached granulite facies conditions throughout the southeastern part of the region (Fig. 1), with amphibolite facies conditions in the outer Færinghaven-Godthåbsfjord tract.
2880-3100 Ma.	Intrusion of diorites, tonalites, granodiorites and minor trondhjemites, the protoliths of the <i>Nûk gneisses</i> , polyphase deformation.
2980 Ma.	High grade metamorphism which culminated in granulite facies conditions on Nordlandet.  Intrusion of anorthosite-leucogabbro-gabbro complexes into Malene supracrustal rocks.  Extrusion of subaqueous basic volcanic rocks with related sub-volcanic intrusions, deposition of sediments ( <i>Malene supracrustal rocks</i> ).  Intrusion of basic dike swarms ( <i>Ameralik dikes</i> ).
ca. 3600 Ma.	Metamorphism that reached granulite facies between Færinghaven and Qôrqt, and amphibolite facies in inner Godthåbsfjord. Intrusion of big-feldspar granodiorites and subordinate ferrodiorites ( <i>Amîtsoq iron-rich suite</i> ).
ca. 3750 Ma.	Intrusion (syntectonic?) of voluminous tonalites, the protoliths of the <i>Amîtsoq layered grey gneisses</i> . Intrusion of granite and pegmatite sheets, deformation and metamorphism.
ca. 3800 Ma.	Extrusion of basic and subordinate felsic volcanic rocks, deposition of chemical sediments and subordinate felsic and pelitic sediments, intrusion of gabbroic sheets ( <i>Akilia association</i> ). Correlated with the Isua supracrustal rocks.

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**ISUKASIA AREA—REGIONAL GEOLOGICAL SETTING**  
(Includes Excursion Guide)

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## INTRODUCTION

This brief account of the geology of the Isukasia area (Figure 1) is biased toward the main theme of the itinerary for the area: What has been established about the protoliths of the early Archean rocks of the area—the Isua supracrustal belt and the Amitsoq gneisses?

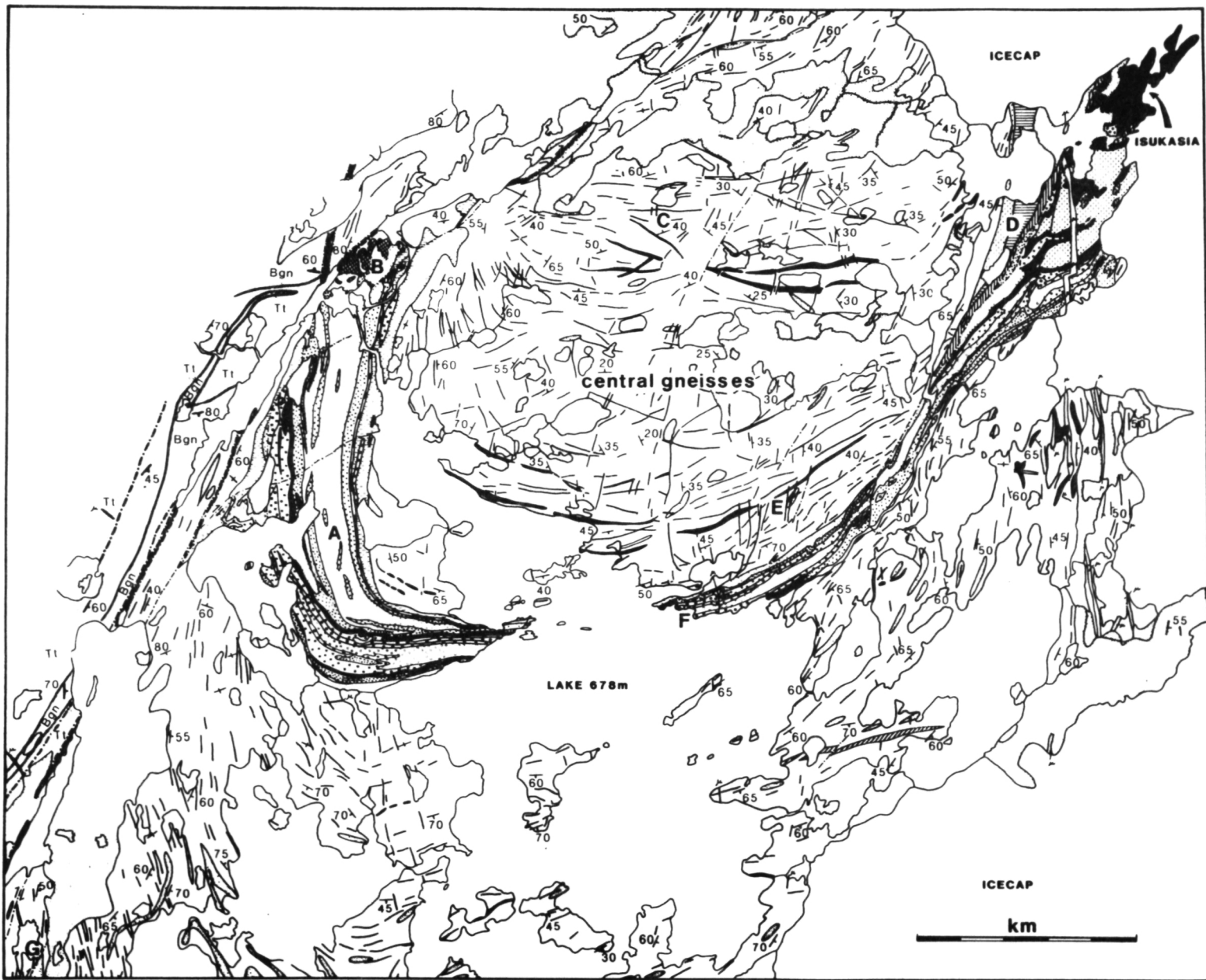
↙ However, it cannot be stressed too much that central to this is the ability to be able to distinguish the structural, geochemical, and isotopic variations of the rocks when they formed from variations impressed upon them during tectono-metamorphic and metasomatic events of early Archean to mid Proterozoic age. Some aspects of this theme are touched upon here; other aspects are dealt with more fully by *Rosing* (1983).

After a visit by a NATO study group to the area in 1978 (*Bridgwater et al.*, 1979), detailed field work was carried out in the area between 1980 and 1982 supported by GGU, the Royal Society, the Carlsberg Fund, and the Danish NRC. The aim of this work was to investigate the lithological variation and the structural and metamorphic history of the Isua supracrustal belt and adjacent gneisses, so that specialized laboratory investigations could be interpreted on a firm geological basis. This field work was built on the regional mapping by the Kryolit Company of Copenhagen (which first discovered the belt in the mid 1960s), reconnaissance studies by GGU geologists (*Bridgwater and McGregor*, 1974), and subsequent GGU mapping at 1:20,000 scale (*Allaart*, 1976).

The Isua supracrustal belt is a 35-km-long tract up to 4 km wide surrounded by and locally intruded by Amitsoq gneisses. It consists of complexly folded, highly deformed middle to upper amphibolite facies rocks patchily retrogressed under lowermost amphibolite to greenschist facies conditions. Mafic, ultramafic, felsic, and quartz-rich inclusions occur throughout the known outcrops of the Amitsoq gneisses and are included under the term Akilia association (*McGregor and Mason*, 1977). The Isua supracrustal belt and the Akilia association probably are derived from a single volcano-sedimentary sequence that was fragmented upon intrusion of the Amitsoq gneisses (e.g., *Baadsgaard et al.*, 1984). Throughout much of the area the Amitsoq gneisses are also highly deformed, but in the central gneisses (Figure 1) there is a region of low deformation in which igneous characters of different phases of the Amitsoq gneisses are locally well preserved.

→ The area's long and complex tectonometamorphic history of events can be divided into episodes using a combination of dike chronology, isotopic, and petrological studies (Table 1). The earliest dikes, the ca. 3700 Ma Inaluk dikes, intrude the earliest (tonalitic) components of the Amitsoq gneisses but are themselves

cut up by the injection of the younger (granitic and pegmatitic) phases of the Amitsoq gneisses of the area (*Nutman et al.*, 1983). In areas of low late Archean deformation, strongly deformed early Archean mafic rocks have coarse-grained metamorphic segregations and are cut by virtually undeformed mid-Archean Tarssartôq (Ameralik) dikes (Table 1) devoid of metamorphic segregations. This shows that the area was affected by regional amphibolite facies metamorphism in the early Archean. Late Archean and Proterozoic metamorphic imprints are marked to very strong in the area (*Rosing*, 1983). Much of the early Archean gneiss complex was already highly deformed when the mid-Archean Tarssartôq dikes were intruded. Within the central gneisses the Tarssartôq dikes locally retain igneous textures and mineralogy but elsewhere are recrystallized to form lineated hornblende-amphibolites that in the Isua supracrustal belt and the gneisses to the south locally contain garnet. After regional ductile deformation and amphibolite facies metamorphism the area was cut by pegmatite dikes at ca. 2550 Ma (*Baadsgaard et al.*, 1985). Thus the post-Tarssartôq-dike amphibolite facies metamorphism(s) and associated strong deformation are correlated with deformation and metamorphism in the other parts of the Godthåbsfjord region that were contemporaneous with and perhaps related to intrusion of the Nûk gneisses and younger crustally derived granitoids between ca. 3050 Ma and 2600 Ma (e.g., *Baadsgaard and McGregor*, 1981; *Robertson*, 1983; *McGregor et al.*, 1983). Members of the Proterozoic dike swarms of West Greenland are found in the Isukasia area. They are locally cut by shear zones, in which they develop lowermost amphibolite to greenschist facies assemblages but are otherwise undeformed. Detailed petrological studies and isotopic interpretations have shown that the Isua supracrustal rocks locally recrystallized and severely reacted with hydrous fluids during a Proterozoic amphibolite facies event at ca. 1800 Ma and that kyanite developed in shear zones late in the area's development (*Rosing*, 1983). This means that, added to the complication of nearly total recrystallization in the late Archean, kyanite-bearing assemblages in the Isua supracrustal belt (in the vicinity of Proterozoic shear zones) cannot be used with certainty to determine > 3600 Ma thermal gradients in the supracrustals (see *Boak and Dymek*, 1982). Fluid movement and recrystallization at ca. 1800 Ma is probably associated with major faulting concentrated in the western part of the area (e.g., *Nutman*, 1982). *Kalsbeek et al.* (1980) recorded a ca. 1600 Ma old granite dike that cuts the Isua supracrustal belt.



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Table 1. Chronological sequence in the Isukasia area

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- (10) (youngest) Injection of basic dykes and crustally derived granite sheets. Faulting under lowermost amphibolite facies to greenschist facies conditions, and metasomatism. 1600 to 2100 Ma.
- (9) Intrusion of pegmatites; ca. 2550 Ma.
- (8) Development of a strong banding with local isoclinal folding (only recognized in the south of the area) followed by linear belts of strong deformation interspersed with southerly plunging folds with wavelengths of up to more than 10 km. Amphibolite facies metamorphism. Local intrusion of granitic-granodioritic sheets. 2600 to 3100 Ma.
- (7) Intrusion of Tarsartôq dykes, probably equivalent to the Ameralik dykes in Godthåbsfjord; ca. 3200 Ma.
- (6) Deformation giving rise to upright folds.
- (5) (c) Intrusion of pegmatic gneisses (ca. 3400 Ma) and thin trondhjemitic sheets. (b) Intercalation of supracrustal and gneiss units. (a) Deformation to produce a strong banding, most important in the south. It is possible that a, b, and c were contemporaneous.
- (4) Intrusion of the white gneisses; 3650–3600 Ma.
- (3) Intrusion of the Inaluk dikes.
- (2) Intrusion of the grey gneisses. This group probably includes early thin tonalitic sheets discussed in *Nutman et al.* (1983). Isoclinal folding of supracrustal rocks (1) may have occurred during intrusion of the grey gneisses; 3750–3700 Ma.
- (1) (oldest) Formation of the Isua and Akilia association supracrustal rocks and intrusion of basic and ultramafic rocks into them; ca. 3800 Ma.
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## ISUA SUPRACRUSTAL BELT

The Isua supracrustal belt (Figure 1) is the largest fragment of ca. 3800 Ma sedimentary and volcanic rocks known. As it comprises the oldest rocks so far discovered, it has attracted considerable interest and detailed research on important aspects of crustal evolution. Because of the antiquity of these rocks and their significance to the study of the early crust, it is tempting to present information from them as giving definitive answers. However, the strong modification of these rocks since their formation means that they are not nearly so well preserved as somewhat younger sequences, such as those in Western Australia. Indisputable sedimentary structures are only preserved in exceptional exposures and are in all cases markedly deformed. The most reliable

age of deposition of the Isua supracrustal rocks is  $3812^{+21}_{-14}$  Ma (*Baadsgaard et al.*, 1984; U/Pb concordia intercept for zircons from sediment derived from acid volcanic rocks). The Rb-Sr, Pb-Pb, and Sm-Nd systems give ages of over 3600 Ma but are disturbed by several periods of Archean and Proterozoic metamorphism (*Rosing*, 1983). A summary of early studies of the Isua supracrustal belt is given by *Nutman et al.* (1984).

Early studies showed that the belt consists of layered supracrustal units of detrital, chemical sedimentary, and volcanic origin interdigitated with Mg-Al-rich, massive chlorite leucoamphibolites (the garbenschiefer units), and ultramafic units (dunites, peridotites, and their hydrated and carbonated equivalents). A coherent

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Fig. 1. Geological sketchmap of the Isukasia area. Localities of A–G are described in the text. (1) Undifferentiated cover; (2) Proterozoic dyke; (3) Tt-Mid Archean Tasersuaq tonalite; 3 Bgn Archean banded gneisses; (4) Tarsartôq dykes; (5) Amîtsoq gneisses; (6) A6 felsic formation; (7) A5 calc-silicate formation; (8) A4 upper banded iron formation; (9) A3 variegated schist formation; (10) A2 lower banded iron formation; (11) A1 amphibolite formation; (12) Undifferentiated A3–A1; (13) B2 mica schist formation; (14) B1 felsic formation; (15) garbenschiefer amphibolite; (16) ultramafic rocks; (17) Akilia association inclusions; (18) foliation/compositional layering; (19) fault; (20) late Archean (2550 Ma) pegmatite.

stratigraphy (Sequence A) has been established throughout the length of the Isua supracrustal belt and is shown to be repeated about isoclinal folds (*Nutman et al.*, 1984). It is impossible to estimate original thicknesses of individual units because of strong deformation. Excluding units of garbenschiefer and ultramafic rocks, the supracrustal sequences total less than 1 km. The garbenschiefer and ultramafic units transgress lithological divisions in the supracrustal sequence, and the garbenschiefer contains inclusions or screens of metasedimentary rocks. Both these lithologies are interpreted as intrusions into a volcano-sedimentary sequence. Sequence A is divided into formations designated by the dominance at different stratigraphic levels of the sequence by different lithologies: (in ascending order) A1 amphibolite formation, A2 lower banded iron formation, A3 variegated schist formation, A4 upper banded iron formation, A5 calc-silicate formation, and A6 felsic formation. Likewise, Sequence

B (restricted to the eastern part of the belt) is divided into: (in ascending order) B1 felsic formation and B2 mica schist formation (Figure 2). The way-up of these sequences is based on facing determinations on graded layers of felsic metasediment. A full description of the stratigraphy is given by *Nutman et al.* (1984).

The Isua supracrustal sequences (and Akilia association units of the area) are dominated by interlayered sediments of diverse parentage, and altered, banded basic rocks of igneous parentage (Figure 2; Table 2). Unaltered igneous rocks are rare apart from those that are clearly of intrusive origin. Supracrustal units show marked lateral variation in their lithotype and chemical composition. All terrigenous sediments are interpreted as derived from volcanic sources. There is no field or isotopic evidence that older sialic basement or emerging granite plutons contributed to the clastic material. The felsic rocks were probably derived from dacites that underwent alteration (possibly subaerial weathering) at

Table 2. Representative analyses Isukasia area early Archean supracrustal rocks

Sample	225996	292107	158497	67690	58526c	167655	171756	175554	117988a
SiO <sub>2</sub>	50.01	87.19	13.74	57.34	66.56	60.92	45.58	49.85	38.84
TiO <sub>2</sub>	1.17	0.04	n.d.	0.39	0.51	0.67	0.22	0.31	0.03
Al <sub>2</sub> O <sub>3</sub>	13.76	n.d.	0.05	16.59	16.34	15.45	15.33	17.08	0.38
Fe <sub>2</sub> O <sub>3</sub>		10.87	1.18	10.97	0.77	2.19	2.01	0.16	1.73
FeO	15.34		4.07	7.55	3.16	4.29	7.31	9.47	6.00
MnO	0.26	0.11	0.59	0.40	0.07	0.14	0.18	0.25	0.12
MgO	5.52	0.76	16.80	2.64	1.21	2.46	16.30	10.40	48.90
CaO	10.21	0.34	28.22	0.85	2.96	6.08	7.83	7.71	0.09
Na <sub>2</sub> O	1.94	0.01	n.d.	0.29	1.63	2.43	0.78	1.36	n.d.
K <sub>2</sub> O	0.36	0.10	0.01	1.37	5.86	2.72	0.07	0.10	n.d.
LOI	0.83	2.50	0.22	2.20	0.94	0.92	4.65	1.88	3.27
CO <sub>2</sub>			35.06		0.65	1.16			
Total	99.50	99.40	100.11	100.67	100.84	99.52	100.30	98.59	99.45
Rb	1	2	n.d.	65	145	120	n.d.	4	n.d.
Sr	90	n.d.	23	30	75	55	55	61	n.d.
Ba	34	6	60	84	430	182	21	n.d.	27
Y	27	2	9		5		10	16	n.d.
Zr			4	113	164	175	18	28	n.d.
Pb			10		26		1	9	1
Th				1					
Cu			n.d.	38	n.d.	55	n.d.	16	n.d.
V	274	9		98		73		137	
Ni	29	35	6	205	23	85	540	160	3975
Cr	55	28	20	500	65	155	1090	279	1040

225996 - banded amphibolite, upper part of amphibolite formation; 292107 - silica-rich banded iron formation, western part of the upper banded iron formation; 158497 - carbonate rock with calc-silicate layers, upper part of the calc-silicate formation; 167690 - garnet-mica schist, upper part of the mica schist formation; 158526c - layered felsic rock, felsic formation of sequence A; 167655 - layered felsic rock, felsic formation of sequence B; 171756 and 175554 - mafic and felsic garbenschiefer amphibolite unit, respectively; 117988a - metadunite. All these rocks come from the Isua supracrustal belt.

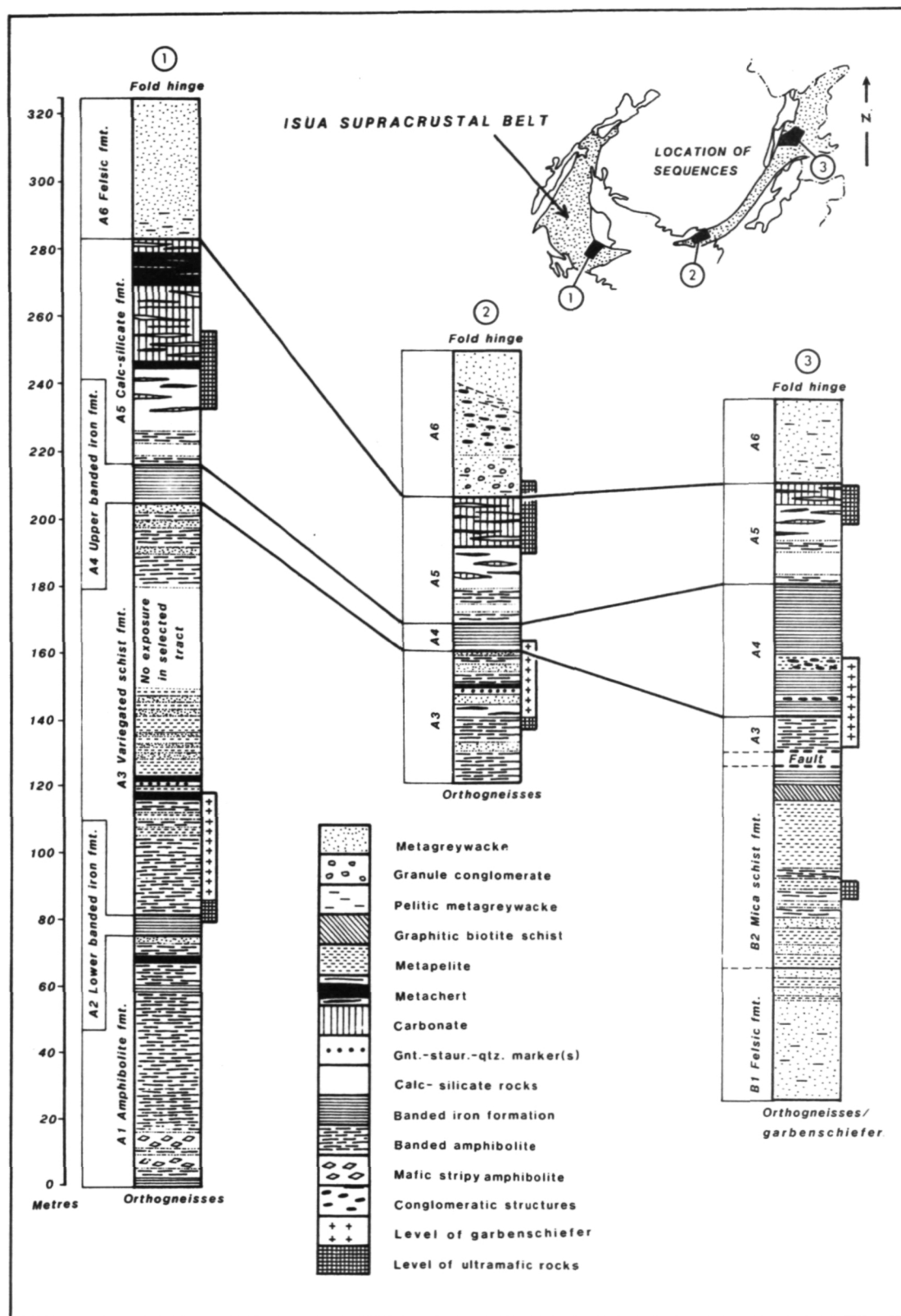


Fig. 2. Schematic stratigraphy for the Isua supracrustal belt.



the time of deposition. Layered amphibolites are interpreted as derived from basic tuffs or from altered basalt and are predominantly of high-Fe tholeiite affinity. Mica schists are interpreted as derived from either weathered basic rocks or from basic tuffs that interacted with water at the time of deposition. The presence of graded bedding and chemical sediments such as banded iron formation and carbonates throughout the succession favors that at least some deposition was subaqueous. Water depths are unknown, but features such as lateral facies changes and possible flat pebble conglomerate units favor shallow water conditions with occasional shoals. The intimate association of chemical sediments with terrigenous material occurs on all scales down to that of individual beds. Bouma-type layering preserved in some of the felsic sediments shows that deposition of some of them was from turbidite flows.

The presently favored model for the Isua depositional environment (*Nutman et al.*, 1984), is of a predominantly submarine volcanic area. There is no evidence that the sequence formed on a basement of older sialic crust. Water depths for a least part of the time were shallow. The topography was subdued apart from volcanic centers. Intermittent volcanic activity and associated instability produced clastic sediments, which alternate and in some cases coincide with deposition of chemical sediments.

## AMÏTSOQ GNEISSES

Amitsoq gneisses envelop the Isua supracrustal belt (e.g., *Bridgwater and McGregor*, 1974; *Nutman et al.*, 1983). Deformation in the gneisses is heterogeneous, such that they range from a weakly deformed, polyphase, sheeted meta-igneous complex to strongly banded or schlieric gneisses in which individual phases can no longer be identified with certainty (similar banded gneisses form at least 80% of the early Archean outcrop in West Greenland). In parts of the Isukasia area the regional early tonalitic gneisses and granitic gneiss sheets are virtually undeformed and preserve their intrusive characters. These are the best preserved very early Archean plutonic rocks known.

Published isotopic studies of Amitsoq gneisses from the Isukasia area are mostly based on the highly deformed, generally well banded lithologies close to the Isua supracrustal belt. Using the Pb-Pb and Rb-Sr systems, ages of ca. 3750 to 3600 Ma have been obtained from them with crustal residence prior to 3600 Ma of not more than 200 m.y. suggested (e.g., *Moorbath et al.*, 1972). Recent Sm-Nd, U-Pb, and Rb-Sr studies based on suites comprising individual phases of Amitsoq gneisses (*Hamilton et al.*, 1983; *Baadsgaard et al.*, 1983

and personal communication, 1982, 1984) do not give evidence that any phase of the gneisses is older than the Isua supracrustal belt. They suggest that the early grey tonalitic phases are ca. 3750 Ma old, the intrusive white granite sheets are ca. 3650 Ma old, and that a younger group of pegmatites separated in the field are ca. 3400 Ma old. Thus the sequence of intrusion of different phases of Amitsoq gneiss spanned as long as 400 Ma (Table 1).

The least deformed Amitsoq gneisses occur in the core of the central gneisses (Figure 1), which is the best area for investigating these rocks. Even the best preserved of the gneisses have been subject to some recrystallization and isotopic disturbance during the late Archean and Proterozoic events (P.N. Taylor, unpublished Pb-Pb data; *Baadsgaard*, 1983; and unpublished Rb-Sr, Pb-Pb, Th-Pb, and U-Pb data). The two main groups of gneiss (older, tonalitic grey gneisses and younger, granitic white gneisses) are separated in time by intrusion of mafic dikes (the Inaluk dikes; Table 1). The chronology given in Table 1 is probably applicable for the generally much more deformed gneisses south of the Isua supracrustal belt, because in augen of low deformation there, grey gneisses are cut by Inaluk dikes and then by white gneisses (*Nutman*, 1982).

The grey gneisses are tonalites apart from rare granodiorites and quartz diorites (Figure 3; Table 3). They form about 70% of the central gneisses. They are polyphase, consisting of rafts of mafic tonalite occurring in more voluminous pale tonalite. A plausible origin for the protoliths of the grey gneisses would be partial melting (at depth) of basic rocks like those in the Isua supracrustal belt and Akilia association. Where least deformed they have a schlieric biotite banding and are plagioclase phyric. Hornblende, which is present only in more mafic units, lies within the schlieric biotite fabric and coexists with biotite. Sericitization of plagioclase, rimming of hornblende by either pale amphibole or fine-grained biotite, local breakdown of biotite to white mica, and also overgrowths of epidote and zoisite are widespread. These features are attributed to events ranging in age up to the mid-Proterozoic. Locally, grey gneisses cut by Inaluk dikes contain inclusions of Akilia association (*McGregor and Mason*, 1977) or Isua-type supracrustal rocks (*Nutman et al.*, 1983). Sheets of tonalitic gneisses intrude the Isua supracrustal belt (*Moorbath et al.*, 1977) and other supracrustal units in the area. These sheets are interpreted as equivalent to the regional grey gneisses. Grey gneiss sheets are sparsely distributed through most of the Isua supracrustal belt and other large supracrustal units in the area, even where they lie adjacent to units dominated by grey gneisses. Contacts of supracrustal units not complicated by

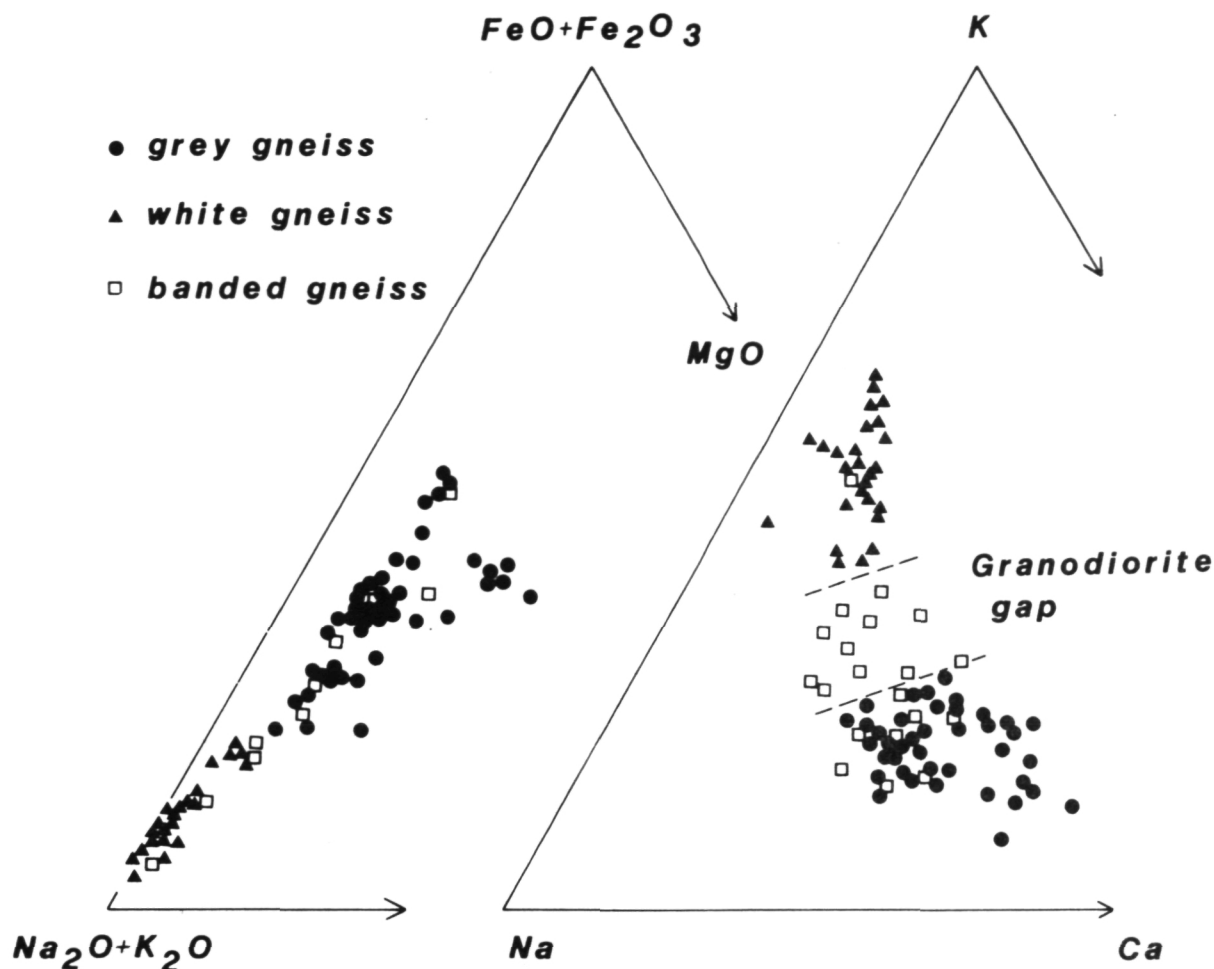


Fig. 3. Compositional variation of the Amitsoq gneisses in the Isukasia area.

intrusion of ca. 3400 Ma pegmatites are sharp, with biotite banding in the grey gneisses parallel to the contacts. These contacts are interpreted as early to middle Archean faults, possibly rotated thrusts (Nutman, 1984).

The Inaluk dikes are sparsely distributed and intrude the grey gneisses. Inaluk dikes have not been found in the major supracrustal units such as the Isua supracrustal belt, but at two localities agmatized mafic amphibolite, probably of supracrustal origin, is cut by them. Inaluk dikes (Table 3) are fine-grained, mafic, biotite- and hornblende-bearing, dioritic intrusions normally less than 2 m wide, that in the least deformed parts of the central gneisses are steeply inclined. They commonly have irregular, cusped margins, suggesting that they were plutonic dikes. There are several bands of coarse-grained, clinopyroxene-bearing mafic amphibolite that are up to 100 m wide and are generally heavily agmatized by pale gneisses, that may be intra-Amitsoq mafic-ultramafic intrusions, perhaps related to the Inaluk dikes.

The Inaluk dikes are interpreted as being derived from fractionated basic melts of mantle origin.

The white gneisses are a polyphase swarm of anastomosing sheets generally less than 25 m thick that cut the grey gneisses. In the northeast of the central gneisses they coalesce to form a single lens that underlies about 10 km<sup>2</sup>, whose center is devoid of grey gneiss inclusions. In contrast, white gneisses are particularly scarce in the northeast of the central gneisses. Overall, the white gneisses form about 30% of the central gneisses and a lower percentage of the gneisses south of the Isua supracrustal belt. The white gneisses are medium to coarse biotite, muscovite granites that grade into potassic granodiorite locally (Figure 3; Table 3). There are some pegmatite veins that preceded intrusion of the large volumes of granitic white gneisses, and pegmatite also occurs as selvages to granitic white gneiss sheets. Biotite is less than 10% modal and forms a crude gneissosity, accentuated in some cases by elongate biotite-rich smears up to 5 mm thick.

Table 3. Representative analyses of Amitsoq gneisses

Sample	237000	236991	236966	236955	236949	229472	292192	236961	236928
SiO <sub>2</sub>	64.12	68.02	71.72	72.64	47.45	74.16	67.10	69.31	71.70
TiO <sub>2</sub>	0.47	0.41	0.27	0.17	0.95	0.01	0.39	0.35	0.24
Al <sub>2</sub> O <sub>3</sub>	14.76	15.22	14.60	14.40	11.31	14.25	15.94	15.50	14.40
Fe <sub>2</sub> O <sub>3</sub>	2.22	1.29	0.40	0.25	3.42	n.d.	0.80	0.67	0.42
FeO	5.12	2.66	1.46	0.99	8.90	0.44	2.69	3.01	2.36
MnO	0.08	0.04	0.03	0.02	0.23	0.01	0.06	0.06	0.04
MgO	1.25	1.17	0.45	0.25	10.64	0.01	0.99	0.75	2.81
CaO	4.51	3.66	1.86	1.45	9.60	0.85	2.52	2.98	2.36
Na <sub>2</sub> O	3.77	4.62	4.02	3.94	1.65	2.24	4.65	4.87	4.34
K <sub>2</sub> O	1.92	1.41	3.74	4.73	2.77	6.30	2.88	1.47	2.21
LOI	0.92	0.71	0.71	0.54	1.26	0.15	0.86		
CO <sub>2</sub>									
P <sub>2</sub> O <sub>5</sub>	0.21	0.14	0.08	0.06	0.51	0.1	0.13	0.11	0.07
Total	99.35	99.35	99.34	99.44	98.69	98.42	99.01	99.08	100.88
Rb	64	87	141	116	69	225	154	192	119
Sr	267	263	224	118	189	70	340	191	195
Ba	334	199	626	567	2054	270	551		
Y	26	20	6	7	28	n.d.	10	12	9
Zr	158	169	212	151	89	18	160	167	129
Pb	12	17	27	28	11	110	31	18	24
Th	1	4	16	18	6	4	5	5	11
Cu	29	16	6	2	26	n.d.		8	
V	46	35	20	12	223	1	33		
Ni	6	2	n.d.	n.d.	126	2	10		
Cr	15	14	4	3	598	7	21		
La	19.2	16.9	45.2	39.6	37.2				
Ce	40.0	38.6	91.7	56.7	83.7				
Nd			20.1	16.2					
Sm	4.92	4.24	3.64	3.12	10.20				
Eu	1.65	0.926	0.728	0.580	2.73				
Gd									
Tb	0.754	0.436	0.251	0.179	0.844				
Dy									
Er									
Yb	1.80	1.33	0.205	0.336	1.400				
Lu	0.242	0.187	0.092		0.200				
Hf	4.12	4.35	5.63	4.13	3.61				

237000 - Mafic grey gneiss, southern central gneisses; 236991 - typical grey gneiss, southern central gneisses; 236966 and 236955 - typical white gneisses, northern central gneisses; 236949 - Inaluk dike, northern central gneisses; 229472 - banded gneiss, ca. 5 km south of the Isua supracrustal belt; Grey gneiss inclusions in white gneisses, 236961 - distinct margins; 236928 - blurred margins

In the core of the central gneisses (where deformation is least), the white gneisses are predominantly gently inclined and commonly break up the grey gneisses into lozenge-shaped rafts. It is likely that in this low deformation area the white gneiss sheets have not been significantly rotated since their intrusion. Inaluk dikes are commonly displaced laterally across white gneiss sheets, and where least deformed, a schlieric flow fabric

is preserved in the white gneisses that is not seen in the grey gneisses. The characteristics of the white gneisses described above suggest that they were intruded at the present level of exposure as inclined sheets (dipping less than 40°), synchronous with lateral displacements. Commonly grey-white gneiss contacts are slightly blurred with a thin biotite-rich selvage. Grey gneisses that occur as inclusions in or close to very large units of white



gneisses are coarsely recrystallized. In extreme cases, inclusions take on a ghost-like appearance. Some chemical changes to the grey gneisses during intrusion of the white gneisses include LREE enrichment, HREE depletion, and enrichment of Pb, Th, and Rb (Nutman and Bridgwater, unpublished data). The composition of the white gneisses shows that they could be early stage, low temperature melts. The host of the white gneisses is ~80% grey gneisses and ~20% supracrustal rocks consisting of amphibolites with subordinate ultramafic rocks, felsic gneisses, mica schists, metaquartzites, and banded iron formation. Thus a possible origin for the white gneisses is partial melting (at depth) of predominantly grey gneisses, with a minor contribution from supracrustal felsic rocks and mica schists.

The pegmatitic gneisses are leucocratic, muscovite- and biotite-bearing quartzofeldspathic sheets ranging from granite to quartz-albite in composition. Although generally coarse grained, some sheets contain garnetiferous microgranite that grades into the more typical pegmatite material. They are a volumetrically unimportant component of the gneiss complex and generally occur as sheets less than a few meters thick. Thicker units occur along some lithological boundaries, such as the borders of the Isua supracrustal belt, where they commonly have a flaser texture. It is possible that the pegmatitic gneisses were intruded during a period of deformation, with movement concentrated into certain zones, such as the boundaries of supracrustal units (Nutman, 1984). The pegmatitic gneisses may have originated from granitic magma, which interacted with alkali-bearing fluid and country rocks during crystallization, to give rise to the Na-enrichment trend. Rb-Sr isotopic studies of separate units of pegmatitic gneisses from the Isua supracrustal belt (Baadsgaard *et al.*, in preparation) show that they have the same age within error (ca. 3400 Ma) but markedly different initial  $^{87}\text{Sr}/^{86}\text{Sr}$  values (in one case, more than 0.8!).

Banded gneisses with a well-developed biotite foliation are the dominant gneiss lithology adjacent to and south of the Isua supracrustal belt. They are generally finer grained than their less deformed white and grey gneiss equivalents in the central gneisses, probably due to their greater degree of deformation during recrystallization under amphibolite facies. The banding of these gneisses comes from two main sources. First, a large scale (generally over 50 mm) banding is caused by intense deformation that has reduced the grey and white components to more or less parallel bands, with obliteration of intrusive relations. Second, there is a smaller scale banding and lensoid structure in the grey gneiss components. This is a partial separation into biotite-rich melanosome and quartzofeldspathic leuco-

some, probably the result of recrystallization under upper amphibolite facies metamorphism.

Strongly banded gneisses from early studies in the area (mostly Bridgwater, unpublished) have a wider spread of composition than the grey gneiss samples from areas of lower deformation (Figure 3), and form a "calc alkali" tonalite-granite variation trend (see also McGregor, 1979). There are now more than 60 samples of single-phase grey and white gneisses from the area. None of these samples fall in the 'granodiorite gap' of Figure 3, where many banded gneisses plot. This suggests that the variation trend of the banded gneisses could be due to mechanical mixing of grey gneisses veined by white gneisses and by metamorphic segregation, during early and late Archean amphibolite facies metamorphism. These processes allow samples of a few kilograms to contain several bands of grey and white gneisses or to be heterogeneous due to some degree of segregation into granitic leucosome and mafic melanosome.

The early Archean gneiss complex of the Isukasia area demonstrates that the oldest known continental crust is of polyphase, polygenetic igneous origin. The grey gneisses show that at the start of the geological record the juvenile 'continental' crust was of typical Archean common tonalite composition. It is possible that the white gneisses formed by partial melting of sialic crust dominated by rocks resembling the presently exposed grey gneisses. High heat production from radioactive decay in the early Archean, tectonic uplift of crustal segments, or increase in  $\text{H}_2\text{O}$  content in the source region are all possible contributory factors to initiate partial melting deep in the crust, generating the white gneisses. The white gneisses are ca. 100 Ma younger than the grey gneisses. They are probably products of reworking of early Archean sialic crust by partial melting. The somewhat younger pegmatitic gneisses probably record further purging upwards of low temperature melting fractions of the crust, and their wide variation in composition is attributed to modification of granitic melts by interaction with their country rocks and with fluids. The grey gneisses, white gneisses, and pegmatitic gneisses were intruded over a span of ca. 400 Ma. There is no compelling evidence that their formation should be grouped together as a single protracted 'super-event.'

## ISUKASIA AREA LOCALITY DESCRIPTIONS

The amount that can be seen in the Isukasia area in mid-June is highly dependent on how much winter snow is left lying. For this reason, several localities of interest that are on NW-facing slopes are omitted since there is almost 100% chance that they are under

snowdrifts. Furthermore, restrictions are imposed by the landing requirements of the large helicopter used on this excursion. Several localities demonstrate rocks of the Isua supracrustal belt. The Amîtsoq gneisses are shown where they are virtually undeformed and then traced out into areas where they are progressively modified by early and late Archean tectonometamorphic events. Rocks very strongly affected by Proterozoic metasomatism close to the Ataneq fault are shown, and Akilia association rocks are visited.

### **Stop A (short stop)**

The main lithology at this stop is the garbenschiefer amphibolite unit—a high Al-Mg metagabbro that intrudes the interlayered metavolcanics and metasediments of the Isua supracrustal belt. The garbenschiefer here is a chlorite-bearing rock with a moderately well-defined S fabric. Within it are lenses and pods of rusty weathering garnet-biotite schist. These are probably modified inclusions of pelite. Cutting these rocks is a superficially well-preserved Tarssartôq dike. It is virtually undeformed and has large plagioclase megacrysts concentrated near its eastern side. However, petrographic, geochemical, and isotopic data (Wagner, 1982) show the dike to be recrystallized and altered. Very little plagioclase is left in the groundmass of the dike, but scapolite is abundant, with associated strong enrichment of the dike in Cl. The Rb-Sr and Pb-Pb isotopic characters of the dike are somewhat different in two traverses across it, less than 100 m apart (Wagner, 1982). The data point to recrystallization and alteration of the dike in the Proterozoic. This story of Proterozoic alteration has been well documented in this part of the Isua supracrustal belt by field, petrographic, and isotopic studies of the garbenschiefer unit by Rosing (1983). Looking east from this locality, the western part of the central gneisses can be seen. Note the large, warped, in places slightly podded, Tarssartôq dikes.

### **Stop B (short stop)**

This stop shows strongly altered rocks just above the southeasterly-dipping mid-Proterozoic Ataneq fault. Basic rocks are transformed into (locally crenulated) chlorite-amphibole-albite schists. Alteration is so intense that it can be hard to distinguish between the garbenschiefer unit, banded supracrustal amphibolites, and Tarssartôq dikes. An ultramafic unit in the vicinity has been altered in places to soapstone. Carbonate-bearing veins are common. The strong alteration here is correlated with movement on the Ataneq fault. Alteration of this type (although generally not so severe)

is noted throughout the area. For example, the banded iron formation outcrop at Isukasia and the rocks immediately to the southwest overlie a Proterozoic fault of lesser displacement than the Ataneq fault. Retrogression under uppermost greenschist facies, carbonate, and quartz-veining are common close to these faults. Even where faulting is not apparent (e.g., Stop A), partial retrogression under lowest amphibolite to uppermost greenschist facies is common, with associated changes of trace element and isotopic chemistry.

### **Stop C (long stop)**

At this locality in the northern part of the central gneisses we see some of the best preserved Amîtsoq gneisses. Polyphase (3750–3700 Ma), grey metatonalites with a gneissose fabric are cut through by numerous sheets of (3650–3600 Ma) metagranite and associated pegmatite (white gneisses), which have shallow to moderate inclinations to the north. Steeply dipping Inaluk dikes, cut by the white granite and pegmatite sheets occur. Due to the low degree of deformation in the area since ca. 3600 Ma, intrusive relations between the Amîtsoq phases are well preserved and local interaction between the grey tonalites and the white granites can be seen. The gneisses in this general area are virtually free of supracrustal inclusions. Tarssartôq (Ameralik) dikes in this area are undeformed and retain igneous textures.

### **Stop D (long stop)**

This stop is a traverse over sequence B of the Isua supracrustal belt (Figure 1), from its contact with the central gneisses in the west to its contact with sequence A in the east. A garbenschiefer amphibolite unit occurs at the western edge of the felsic formation. Sequence B, particularly its western margin, is intruded by pegmatitic sheets. Some of these have been dated at ca. 3400 Ma (Baadsgaard et al., in preparation). Except for these sheets, the contact between the central gneisses and sequence B is sharp and cuts across the stratigraphy of the sequence (Figure 1); grey gneiss sheets in the supracrustal rocks are rare.

B1 felsic formation consists of generally fine-grained felsic rocks layered on a 20–100 mm scale. Graded beds are locally preserved. Garnetiferous mica schist units occur throughout the formation, increasing in frequency eastwards. To the east, B2 mica schist formation outcrops, forming a scarp. Predominant are chlorite + biotite + garnet + quartz schists that locally contain staurolite, kyanite, carbonate, graphite, and tourmaline. The schists have a faint, but regular layering on all scales. Interlayered are some units of magnetite banded iron

formation, graphite schist, amphibolite, and ultramafic schist.

The contact between sequences A and B is a fault with the same orientation as the Ataneq fault in the west of the area. Alteration is common in its vicinity. For example, rocks of B2 mica schist formation show chloritization of garnet and development of a crenulated schistosity of muscovite locally overgrown by tourmaline.

#### **Stop E (short stop)**

This locality shows somewhat more deformed Amîtsoq gneisses than at locality (C). Strain is mostly early Archean, but with an added component since the Tarssartôq dikes were intruded. Note the 'steepening-up' of layering in the gneisses and rotation toward parallelism of originally strongly discordant Inaluk dikes. Clinopyroxenic amphibolite with subordinate banded grey amphibolite occurs as a train of inclusions, enshrouded in pegmatitic gneiss. These amphibolites are probably of supracrustal origin. Note textures in the grey gneisses locally, which suggest a small degree of metamorphic segregation during or prior to intrusion of the white gneisses. The Tarssartôq dikes at this locality commonly retain igneous textures but are slightly deformed and commonly have altered margins.

#### **Stop F (long stop)**

The purpose of this stop is to show a broad selection of lithologies present in sequence A of the Isua supracrustal belt. Formations upper A3 to A6 (Figure 2) are present as are strongly deformed garbenschiefer and ultramafic units. Pegmatite and grey gneiss sheets are locally present. The sequence of lithologies is corrugated by numerous (2700–2600 Ma) steeply plunging 'Z' folds with a strong fold-axial lineation and is disrupted locally by tectonic slides. A6 is dominated by the felsic nodule lithology. This is most spectacularly developed in the core of a fold on a headland and superficially resembles deformed conglomerate. However, following this unit onto the southern limb of the fold, the pods are seen to be disrupted layers in the sedimentary protolith (this is best seen when the level of the lake is low). Also well displayed here is the carbonate-rich facies of A5, finely laminated A4 banded iron formation, and A5 amphibolites with horizons of quartz-garnet-staurolite rock (A5 being partly included within the garbenschiefer unit). These outcrops show the supracrustal rocks with a fairly typical state of preservation, demonstrating how deformed and recrystallized they are. The Tarssartôq dikes are folded

or podded and consist of hornblende-amphibolites that in some cases contain garnet. This shows the extent of late Archean recrystallization in the Isua supracrustal belt, which, taken as a whole, seems to have been a zone of high strain in the late Archean, relative to the adjacent gneisses.

#### **Stop G (medium stop)**

At this stop we look at Amîtsoq gneisses and Tarssartôq dikes, a Proterozoic fault, and a unit of Akilia association rocks. The Amîsoq gneisses and Tarssartôq dikes have been so strongly affected by late Archean deformation that the dikes are everywhere subconcordant to the layering of the gneisses. Note that there are also units of deformed, post-dike granitoid in the vicinity. As yet it is unknown if these are 3050–2900 Ma in age or younger. The Proterozoic fault is parallel to the Ataneq fault, about 1 km to the west, and dips at ~45° to the southeast. Note retrogression and discoloration of the gneisses in the fault. Total movement is reverse, with a dextral component. A unit of Akilia supracrustal rocks is truncated by the fault. Lithologies include layered amphibolite gneisses, banded amphibolite, banded iron formation, ultramafic lenses, and a unit of chloritic amphibolite that bears strong resemblance to the garbenschiefer unit of the Isua supracrustal belt. As a package, this supracrustal unit may represent upper A1 to A3 formations of the Isua supracrustal belt, inclusive of the garbenschiefer unit. The western margin of the unit and the gneisses adjacent to it have been affected by very strong, pre-Proterozoic-faulting ductile deformation. Banded amphibolites veined by late Archean granitoids that form the western half of the unit are transformed into mica schists containing granitic nodules that superficially resemble deformed conglomerates in places.

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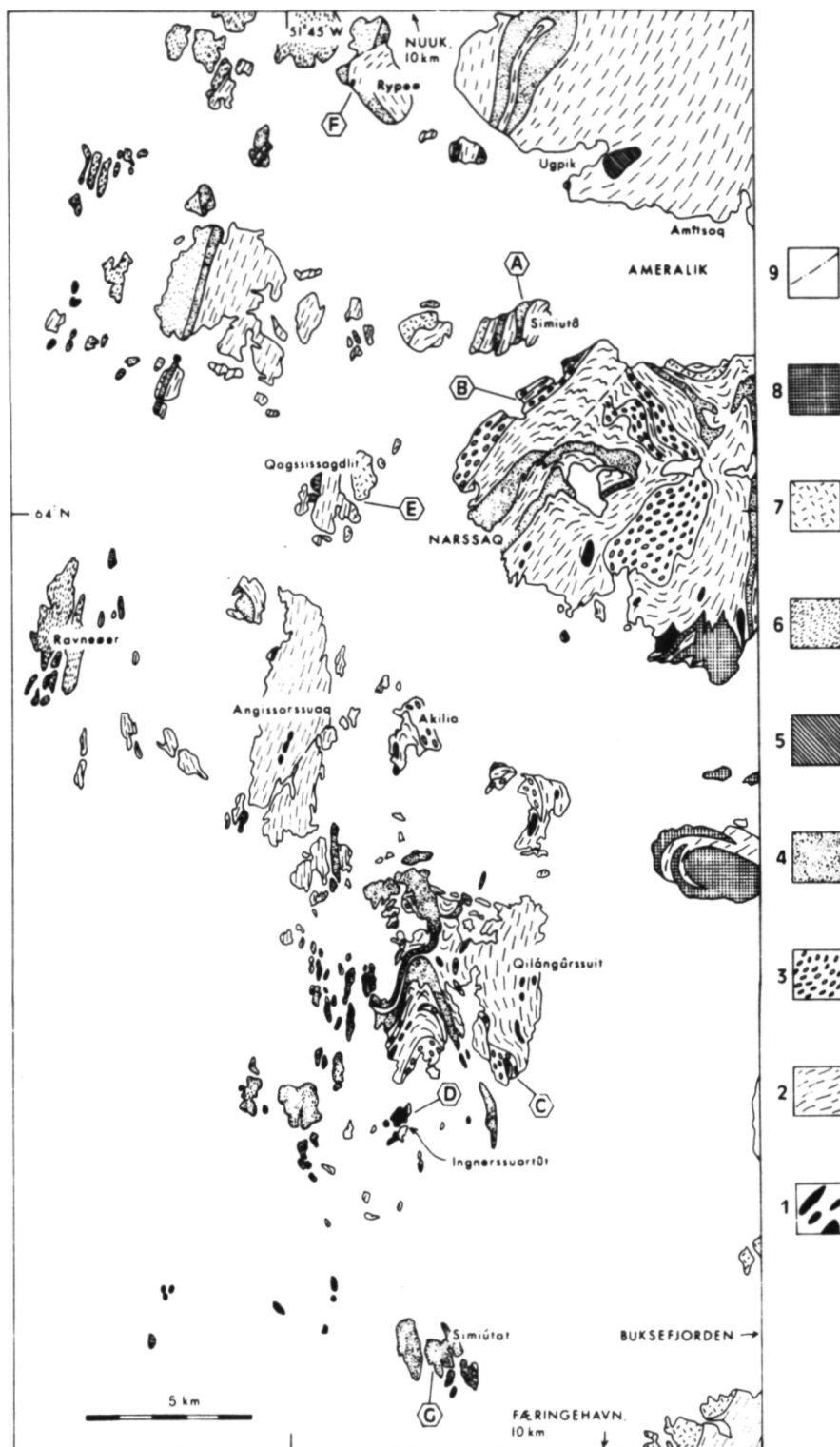


Fig. 4. Geological sketchmap of the outer Ameralik, northwestern Buksefjorden area. A to G, localities described in the text; (1) Akilia association; (2) Amitsôq banded grey gneisses; (3) Amitsôq iron-rich suite, mostly granodiorite; (4) Malene supracrustal rocks; (5) Uggik metadolerite; (6) Nûk gneiss; (7) late Archean deformed granitoids; (8) late Archean undeformed granitoids, probably correlating with the ca. 2550 m.y. Qôrqt granite complex; and (9) Proterozoic fault.

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